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FOREIGN TECHNOLOGY DIVISION

TESTING THE FRICTION OF SLIDING ELECTRIC CONTACTS IN AN ULTRAHIGH VACUUM

by

M. Maillat, F. Aubert,
et. al.

EDITED TRANSLATION

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В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
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М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

GREEK ALPHABET

Alpha	Α	α	*α*	Nu	Ν	ν	
Beta	Β	β		Xi	Ξ	ξ	
Gamma	Γ	γ		Omicron	Ο	ο	
Delta	Δ	δ		Pi	Π	π	
Epsilon	Ε	ε	*ϵ*	Rho	Ρ	ρ	*ϱ*
Zeta	Ζ	ζ		Sigma	Σ	σ	*ς*
Eta	Η	η		Tau	Τ	τ	
Theta	Θ	θ	*ϑ*	Upsilon	Τ	υ	
Iota	Ι	ι		Phi	Φ	φ	ϕ
Kappa	Κ	ϰ κ *ϰ*		Chi	Χ	χ	
Lambda	Λ	λ		Psi	Ψ	ψ	
Mu	Μ	μ		Omega	Ω	ω	

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}

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rot	curl
lg	log

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SWISS LABORATORY OF HORLOGICAL RESEARCH

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TESTING THE FRICTION OF SLIDING ELECTRIC CONTACTS IN AN ULTRA-HIGH VACUUM

TESTING THE FRICTION OF SLIDING ELECTRIC CONTACTS IN AN ULTRAHIGH VACUUM

M. Maillat, F. Aubert, H. E. Hintermann and R. Rocchi

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Prepared by M. Maillat

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1. SUMMARY

This paper presents a study of the behavior of a material for electric contacts with a published composition of 82.5 Ag, 15 MoS_2, 2.5 Cu that slides in a slip ring made of pure silver in regard to friction and wear in an ultrahigh vacuum without a current. The tests were conducted according to the three orientations of the material's structure in order to determine the effect of the direction of friction on it.

The results are greatly diversified. Friction parallel to the structural lines and perpendicular to the direction of pressure results in less wear and wear that is reproducible. These phenomena appear to originate due to flaws in the material's manufacture.

2. INTRODUCTION

In view of the spatial uses of the brush of an electric contact, a sintered material was developed. In accordance with the European Space Research Organisation (ESRO) and European Space Tribology Laboratory [ESTL] the LSRH [Swiss Laboratory of Horlogical Research] was commissioned to study the behavior of this material in an ultrahigh vacuum without a current during the effect of friction and wear. Considering the material's structure, it was interesting to study the effect of orientation on mechanical performance. The results of these tests are presented in the following pages.

3. EXPERIMENTAL PROCEDURE

The test material is a sintered composition obtained by pressure molding with a composition of 82.5 Ag, 15 MoS_2, 2.5 Cu.

It is to be used for making electric contact brushes for spatial applications. The tests took place in an ultrahigh vacuum by rubbing against a pure silver slip ring.

3.1. Preparation of materials

3.1.1. Brushes

The brush material was supplied by the ESTL in the form of 3 disks 31 mm in diameter and 4 mm thick. Its structure is shown in Fig. 1. Three orientations were used for situating the brush relative to the slip ring. The brush's direction being perpendicular to the friction surfaces, a direction had to be selected parallel to the pressure direction and also two others that were perpendicular to each other (Fig. 2).

Actually, there was no difference in the material's structure in the two directions (2 and 3) perpendicular to the pressure. Thus, friction was taken perpendicular to the textural lines in position $\boxed{2}$ and parallel to them in position $\boxed{3}$, as the graphic representation of the orientations, direction of friction and direction of pressure in Figures 3, 4 and 5 show. The indicated friction is the value and the direction of the movement of the slip ring relative to the brush. In the following one the brushes are marked according to their positions $\boxed{1}$, $\boxed{2}$ or $\boxed{3}$ and according to the sample (disk) of molded material from which they were made: 1, 2 or 3. As Fig. 6 indicates, the brushes were cut from the test material for almost all of the tests. Only the brushes for the repeated tests on sample 1 in position $\boxed{1}$, having used up a great deal of material, were cut from other batches of the sample, but always in position $\boxed{1}$.

The brushes were welded onto a brass support. Then they were polished

on emery paper 320, 400, 600,
then by diamond 16, 6, 3, 1 μm,

which gives a CLA [expansion unknown] roughness according to orientation:

brush $\boxed{1}$	0.27 µm CLA
brush $\boxed{2}$	0.20 µm
brush $\boxed{3}$	0.22 µm

3.1.2. Slip rings

The brushes' sliding partners were supplied to the LSRH by Precious Metals S. A., Neuchatel. These are silver disks 50 mm in diameter, 5 mm thick, with a purity of 999.9% that have been shaped and annealed. One new disk per test was provided. Ten disks were issued.

After being polished and cleaned, they were attached mechanically to the support.

Polishing: emery paper 400, then 600
Al_2O_3 3, " 1 µm.
Resulting roughness: 0.065 µm CLA.

3.2. Experimental conditions

Three samples of the material were tested in the three positions without an electric current.

The slip ring disk was set into rotation. The brush was attached and applied with a force of 2.0 N on the flat part of the disk.

The diameter of the friction path is 40 mm.

The linear velocity is 1 m/s, or a rotational velocity of 480 rpm.

Work environment: all of the tests were conducted in an ultrahigh vacuum, the pressure always remaining within 10^{-10} and 10^{-9} Torr.

The brushes and slip rings were cleaned before the tests in a Soxhlet device with a 1:1 solution of toluene and butanol.

The planned duration was 240 hours, or 6,912,000 turns, or 864 km covered.

The measurements taken during the tests:

- coefficient of dynamic and static friction (by the force of the reaction on the brush),
- pressure in the chamber,
- rotation speed,
- number of turns covered,
- brush wear (by the length worn out).

Measurements taken after the tests:

- cross section and examination of the worn surfaces of the brush and slip ring,
- hardness of the materials,
- examination of the structures of the brushes and slip rings.

3.3. Description of the tests

An initial test with a brush 1 $\boxed{1}$ was made in order to check the installation and to be prepared for all the possibilities. It was repeated in the efficient procedural fashion instituted during all initial tests. The results were very close and thus it appeared that reproducibility had been obtained.

Tests of brushes 1 $\boxed{2}$, then 1 $\boxed{3}$ followed, giving wear two and six times greater, respectively, than for the

first two tests 1 $\boxed{1}$. Brush 1 $\boxed{3}$ was so worn out that the test was discontinued on the 7th day.

The program continued, sample after sample and position after position. All of the tests were cut short because of wearing out early. The results were so diversified that it seemed useful to try a brush 1 $\boxed{1}$ again. This time the wear was different again.

4. RESULTS

4.1. Coefficients of friction

The coefficient of static friction was measured several times per test. Table 1 gives the values of it as well as the respective durations of the tests. It shows that the static friction greatly diminished during wear.

The coefficient of dynamic friction was recorded permanently during the tests. The accuracy of the measurement is on the order of ± 0.01. Since this parameter was the occurrence of rapid important oscillations of $\pm$ 10 to 15%, only the mean friction at the point in time of the measurement were retained. These values are shown on Figures 7-10.

It follows from these curves that the friction starts by increasing on a wide scale (on the average it was multiplied by 3) during the first hours of the test. Since wear then adjusts the surfaces between them, the actual contact areas are more important and roughness appears, stabilizing the friction at higher values.

Then friction tends to diminish during the test, while wear increases. It is subject to rapid variations due to rotation and to important fluctuations due to the inhomogeneity of the

Table 1. Coefficients of static friction.

Sample ○ Position □ Test No

Time (days)	① 1 1	① 1 2	① 1 3	① 2	① 3	② 1	② 2	② 3	③ 1	③ 2	③ 3
0	1,0	0,45	1,2	1,25	1,2	1,0	0,88	1,35	0,94	0,70	1,10
1										0,47	0,25
2		0,28					0,23	0,34		0,22	
3				0,31							0,22
4											
5	0,19				0,25	0,29					
6				0,36	0,23		0,26	0,32			0,23
7											
8	0,21	0,35					0,22				
9	0,25										
10				0,22				0,30			

brush material, as becomes apparent from the curves. Neither the brush's orientation nor its original sample seem to affect the coefficient of dynamic friction, which always remains between 0.12 and 0.3 after wear.

4.2. Wear

Table 2 and Fig. 11 represent the wear of the different materials as well as two parameters that might have affected the test: the hardness of the brushes and the slip rings. Some of the brushes were greatly worn; others, very little.

In order to be able to compare these results, only wear determined for 10^6 turns was shown in Fig. 11, a value that all of the tests were at least able to achieve.

Measuring the brushes' wear by weight was a very delicate procedure because of the formation of rough edges and wear grooves, while linear wear permitted measurement throughout the test (Figures 12-14) and resulted in a sufficiently precise total wear value.

The inspection of the wear debris revealed nothing due to their small dimensions.

If the brushes are greatly worn, on the other hand the slip ring disks will only be deformed on the surface; the matter is displaced, not removed, as it appears on the recordings of the cross sections (Figures 15-25).

4.2.1. Variations

Table 2 and Fig. 11 show the differences in behavior during considerable wear. The wear of the brushes varies from 34 to 912 $\mu m/10^6$ turns, or a variation of from 1 to 27.

Table 2. Measurements and analyses (see key on p. 12).

Bru-shes	1 $\boxed{1}$ 1	1 $\boxed{1}$ 2	1 $\boxed{1}$ 3	1 $\boxed{2}$	1 $\boxed{3}$	2 $\boxed{1}$	2 $\boxed{2}$	2 $\boxed{3}$	3 $\boxed{1}$	3 $\boxed{2}$	3 $\boxed{3}$
A	242	243	52,5	243	168	120	195	223	77	47	145
B	697	700	151	700	484	346	561	643	222	136	419
C	284	237	370	355	1400	1595	850	1075	1040	1240	955
D	13	11	22	9	14	24	18	26	36	23	26
E	11	9	14	6,5	25	27	18	27	31	17	25
F	43,8	40,2	61,6	42,5	41,8	42,5	43,0	43,2	40,7	44,1	43,8
G	38,9	38,7	38,2	38,5	37,8	34,6	36,7	35,9	34,2	37,1	34,8
H	1,9	1,6	15	1,3	2,9	6,9	3,2	4,0	16	17	6,2
I	1,6	1,3	9,3	0,9	5,2	7,8	3,2	4,2	14	13	6,0
J	41	34	245	51	289	461	152	167	468	912	228

Key to Table 2:

A - Total number of operation hours
B - Number of turns made $\times 10^4$
C - Wear observed on the brushes, in µm
D - Wear groove of the brush (the distance between the maximum and minimum relief), in µm
E - Groove of the slip ring disk (distance between the maximum and minimum relief), in µm
F - Hardness of the slip ring disk, $HV_{0.3}$, in daN/mm^2
G - Hardness of the brush, $HV_{0.3}$, in daN/mm^2
H - Wear groove of brush, in µm/10^6 turns
I - Wear groove of slip ring, in µm/10^6 turns
J - Total wear of brush, in µm/10^6 turns

By the same token, the relief of the wear grooves (the distance in µm between the most prominent and the deepest parts of the surface, calculated for 10^6 turns) is very variable: from 1 to 13 for the brushes and from 1 to 16 for the slip ring surface.

4.2.2. Effect of orientation

The main goal of these tests was to study the effect of the brush's orientation on behavior during friction and wear in order to determine the best position for use. Despite an apparent dispersion of the results, certain elements stand out.

The recapitulatory table given below shows no matter how the mean wear is calculated for a particular position, a single classification can be established. Position $\boxed{3}$, where friction is in the direction parallel to the material's "grains" on their section, has great regularity of behavior. The minimum/maximum ratio is only 1.7. The mean wear is the least and the maximum represents wear of $2.0 \cdot 10^{-5}$ mm^3/m.

Table 3. Mean wear of brushes for each position.

	Brush	Mean wear N° 1	Wear of brush µm/10^6 turns	Mean wear N° 2
Position $\boxed{1}$	1 $\boxed{1}$ 1	345	41	250
	1 $\boxed{1}$ 2		107 — 34	
	1 $\boxed{1}$ 3		245	
	2 $\boxed{1}$		461	
	3 $\boxed{1}$		468	
Position $\boxed{2}$	1 $\boxed{2}$	372	51	372
	2 $\boxed{2}$		152	
	3 $\boxed{2}$		912	
Position $\boxed{3}$	1 $\boxed{3}$	228	289	228
	2 $\boxed{3}$		167	
	3 $\boxed{3}$		228	

Position $\boxed{1}$, where the friction is parallel to the "grains" of the material on their surface, gives more irregular results: from 1 to 14, with a higher mean.

Position $\boxed{2}$, where the friction, parallel to the direction of pressure, is perpendicular to the "grains" of texture on their section, shows very great variations - from 1 to 18 - and a mean even higher than that for position $\boxed{1}$.

Assuming that the coefficients of friction are identical for the 3 brush positions, one can say that position $\boxed{3}$ gives the best results.

4.2.3. Effect of sample

Calculating the mean observed wear, like in 4.2.2., but this time as a function of the sample, one obtains:

Sample	1	: mean 1	149 $\mu m/10^6$ turns
		mean 2	132 $\mu m/10^6$ turns
	2	: mean	260 $\mu m/10^6$ turns
	3	: mean	536 $\mu m/10^6$ turns

The values go from 1 to 4, while for orientation ($\square$) the means only vary from 1 to 1.5.

Slight differences in the material's preparation (Chapter 5) caused important deviations in the behavior, except for in orientation $\boxed{3}$ of the brush, which was not sensitive to these differences.

4.2.4. Development of wear as a function of time

Figures 12, 13 and 14 represent these variations. The regularity in brushes $\boxed{3}$ is found again. Moreover, the effect of structural changes that are translated here into changes in inclination are observed here for the coefficients of friction as well as for wear.

4.2.5. Wear grooves

Table 2 and Fig. 11 show that the depth of the grooves on the brush and slip ring are often very similar, as might have been expected. These values vary less than the total wear values, but remain slightly related without being proportional.

4.2.6. Hardnesses

4.2.6.1. Brushes

On Table 2 and Fig. 11 it appears that hardness of the brushes depends not on orientation ($\boxed{}$), but rather on the sample:

Sample 1 $HV_{0.3} = 38.4$ daN/mm^2 *
Sample 2 $HV_{0.3} = 35.7$ daN/mm^2
Sample 3 $HV_{0.3} = 35.4$ daN/mm^2.

* 1 daN = 10/9.81 kgf

These values partially explain the superior mean wear life of the brushes made from sample 1 .

4.2.6.2. Slip rings (Fig. 11 and Table 2)

One value is completely different from the others: the hardness of the slip ring used in test No. 3 of brush 1 $\boxed{1}$ is 61.6 daN/mm^2, while the mean of the others is 42.6 daN/mm^2. The unpolished face of the slip ring disks has a mean hardness of 50.3 daN/mm^2.

These important differences originate from the shaping of the slip rings' faces. The disks provided were shaped and annealed; polishing completely removed the layer transformed by shaping (hardening by cold hammering). The slip ring of test 1 $\boxed{1}$ 3 had already been used for another test, it was shaped, polished, but not annealed, resulting in the raised hardness of the surface layer, which might explain the greater wear of the brush for this test than for the other tests 1 $\boxed{1}$.

5. ANALYSES AND EXPLANATIONS OF BEHAVIOR

5.1. Characteristics of brush material

5.1.1. Hardness

The important differences in wear and hardness according to the sample from which the brush was made led us to believe that the method by which the vacuum was obtained, baking at 300°C for 4 hours, might have transformed the material being studied. In order to check this hypothesis, the hardnesses of the brushes from unfinished disks as well as those of parts of the disks that were baked in an oven in a vacuum for 4 hours at 300°C were measured.

Table 4. Hardnesses $HV_{0.3}$ in daN/mm^2 of brush materials.

	Unfinished sample	4 hours at 300 °C	Brushes
1	35,4	38,5	38,4
2	35,2	35,4	35,7
3	36,1	35,3	35,4

Sample 1 was certainly transformed by the treatment; this is what explains the difference in the hardness of brushes 1 and, probably, their superior behavior during wear.

5.1.2. Chemical composition and density

The chemical composition of the raw materials of the samples was determined by two methods with a relative precision of 2 o/oo, one by atomic absorption spectrometry, the silver being calculated by the difference, and the other based on the potentiometric titration of silver. Table 5 shows the synthesis of these two methods. It also shows the values of the measured densities, practical and theoretical, that correspond to the determined

composition as well as the porosity brought out by the difference between the two densities mentioned above.

Table 5. Composition of brush materials.

Samples	1	2	3
Ag % (by weight)	90,8	90,7	90,2
Cu % (by weight)	2,3	2,5	2,7
MoS_2 % (by weight)	6,9	6,8	7,1
Theoretical density	9,67	9,68	9,64
Actual density	8,87	8,77	8,62
Porosity %	8,3	9,4	10,6

An important difference between the sample's actual composition and the published composition can readily be seen on this table. The percentage of MoS_2 is more than two times less than the specified 15%. There is little difference for copper. Thus, there is a greater percentage of silver present.

The variations in composition from one sample to another are no more important than those observed between different parts of the same sample. The values presented above are the mean values of the proportions encountered for each piece analyzed.

The systematic variation in wear from one sample to another seems to be explained by differences in porosity, which are of exactly the same order as those in wear.

Small differences in porosity, around 30% in this case, appear to cause considerable differences in the material's total coherence.

This does not show up in the measurements of hardness of the unfinished disks, since the stamp, which hardly causes more than a "grain" in the material, only squashes the material, unlike friction, which tears it off.

5.1.3. Microphotographs

Micrographs of the brushes and the unfinished samples were taken in order to explain the differences in behavior.

As Figures 26 and 27 show, major flaws were found. These are parts made up entirely of silver; they were flattened out by the pressure. They are more than a millimeter in diameter perpendicular to the pressure and often they are more than 0.25 mm thick.

These spots, having hardness greatly inferior to that of the rest of the material (Fig. 26), can result from the silver being too goarsely ground before stamping, from too much silver, or from a poor mixture of powders.

During rubbing in the ultrahigh vacuum, this pure silver unites with the slip ring, is rapidly torn off of the brush and forms salient reliefs that make the rest of the bruch wear out even more rapidly.

The uncertain presence of these spots in the three samples lies at the root of the dispersion of the numerous results of wear and of the variation in wear through time.

Only orientation $\boxed{3}$, which makes the rubbing parallel to the structural "grains," offers friction that encounters these spots along their smallest dimension, thus limiting their effect. The size of the spot that comes in contact with the slip ring is more than 4 times larger in the two other orientations. Moreover, this orientation attracts the "grains" of the material in the

direction in which they have the least coherence and the porosity has the least effect.

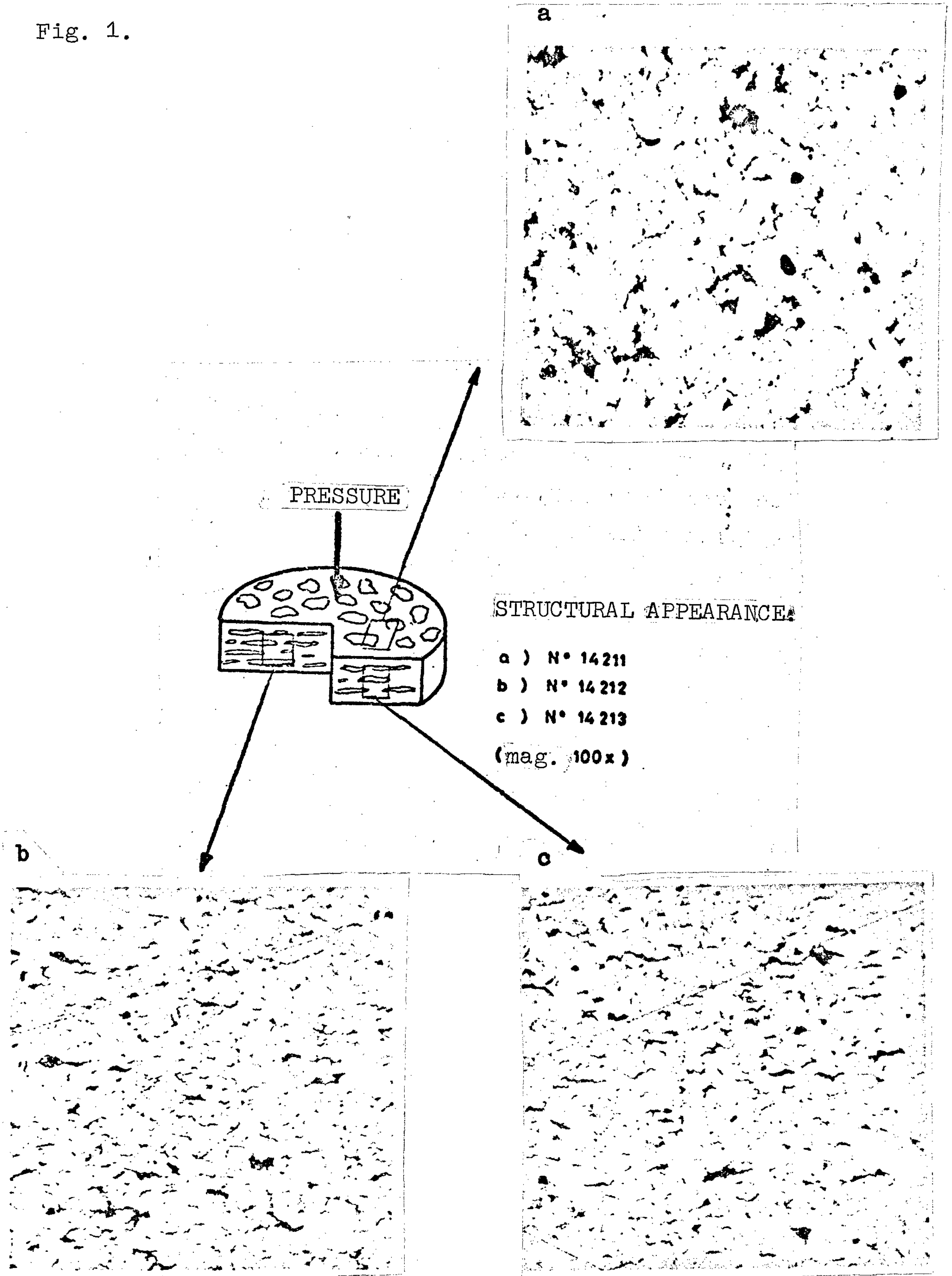
5.2. Slip rings

The structure of the slip rings was also examined, as Fig. 27 shows. It is rather irregular; coarse grains are distributed in a finer structure. This arrangement contributes to the dispersion of the results.

6. CONCLUSIONS

This detailed study makes it possible to confirm that brushes of 90.6 Ag, 2.5 Cu, 6.9 MoS_2 give the best results from the viewpoint of friction and wear when used in an ultrahigh vacuum without an electric current rubbing against silver slip rings if they are used in the position named $\boxed{3}$. The results obtained with the other two orientations can be affected too easily by the material's irregularities.

Fig. 1.


a
PRESSURE
STRUCTURAL APPEARANCE
a) N° 14211
b) N° 14212
c) N° 14213
(mag. 100x)
b
c

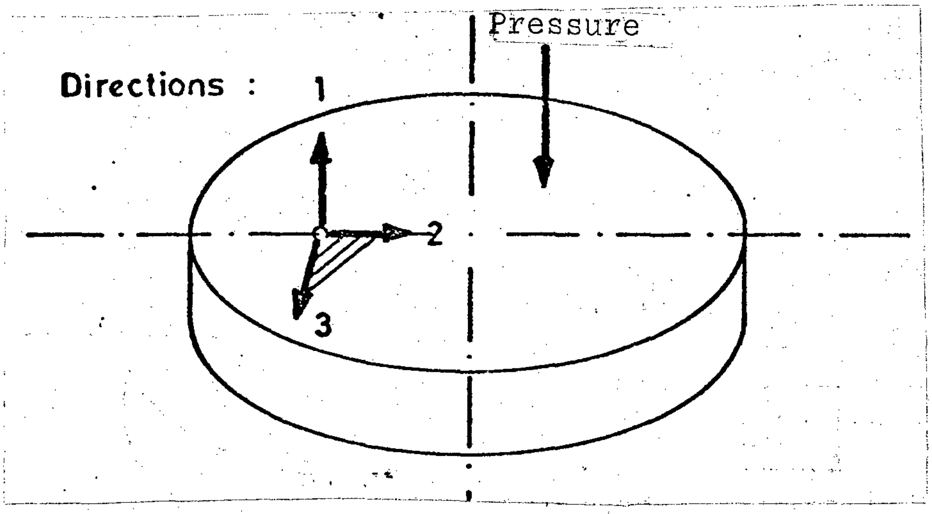


Fig. 2. POSITIONS OF BRUSHES IN SAMPLE

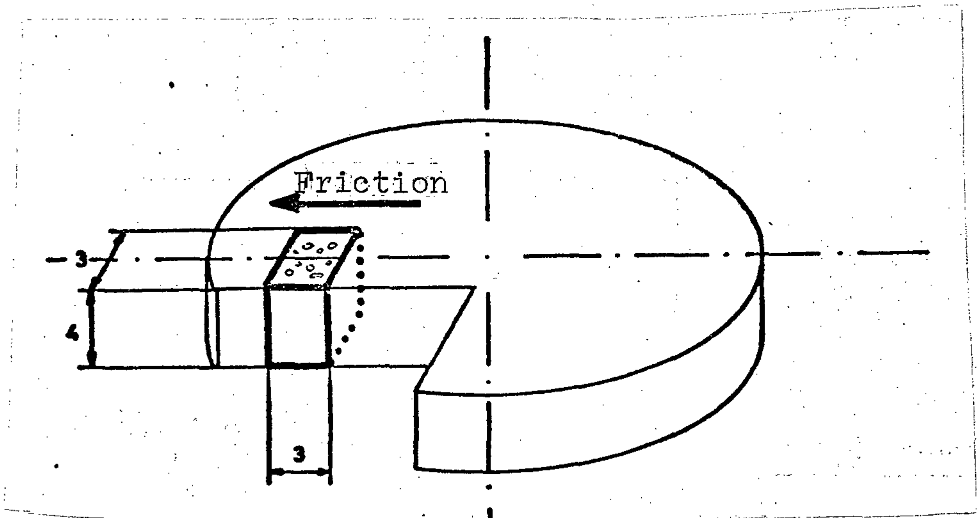


Fig. 3. ARRANGEMENT OF BRUSH IN POSITION 1

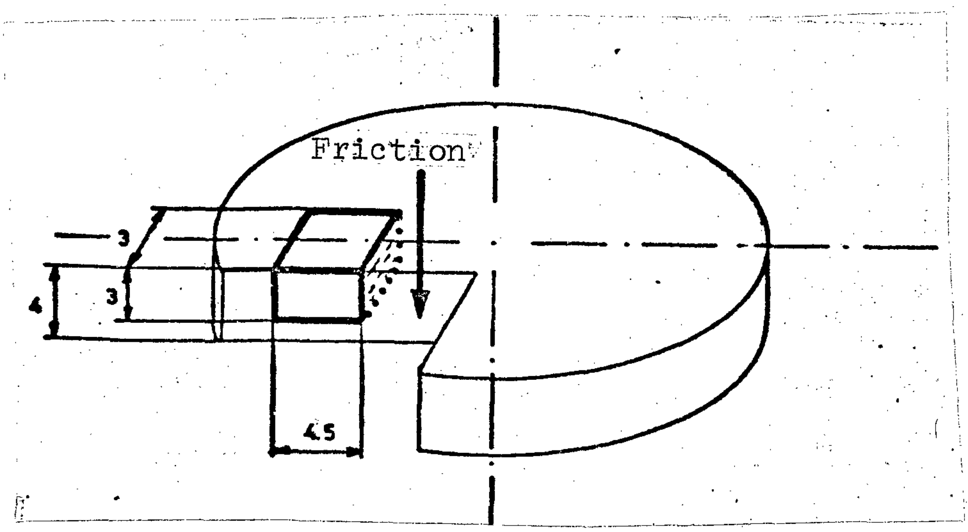


Fig. 4. ARRANGEMENT OF BRUSH IN POSITION 2

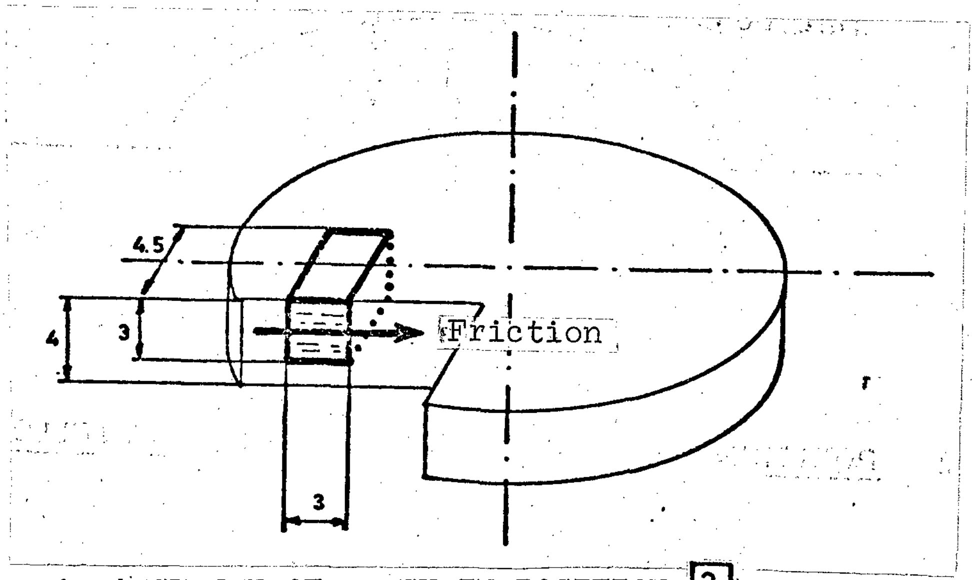


Fig. 5. ARRANGEMENT OF BRUSH IN POSITION 3
the friction is parallel to the textural lines ("grains")

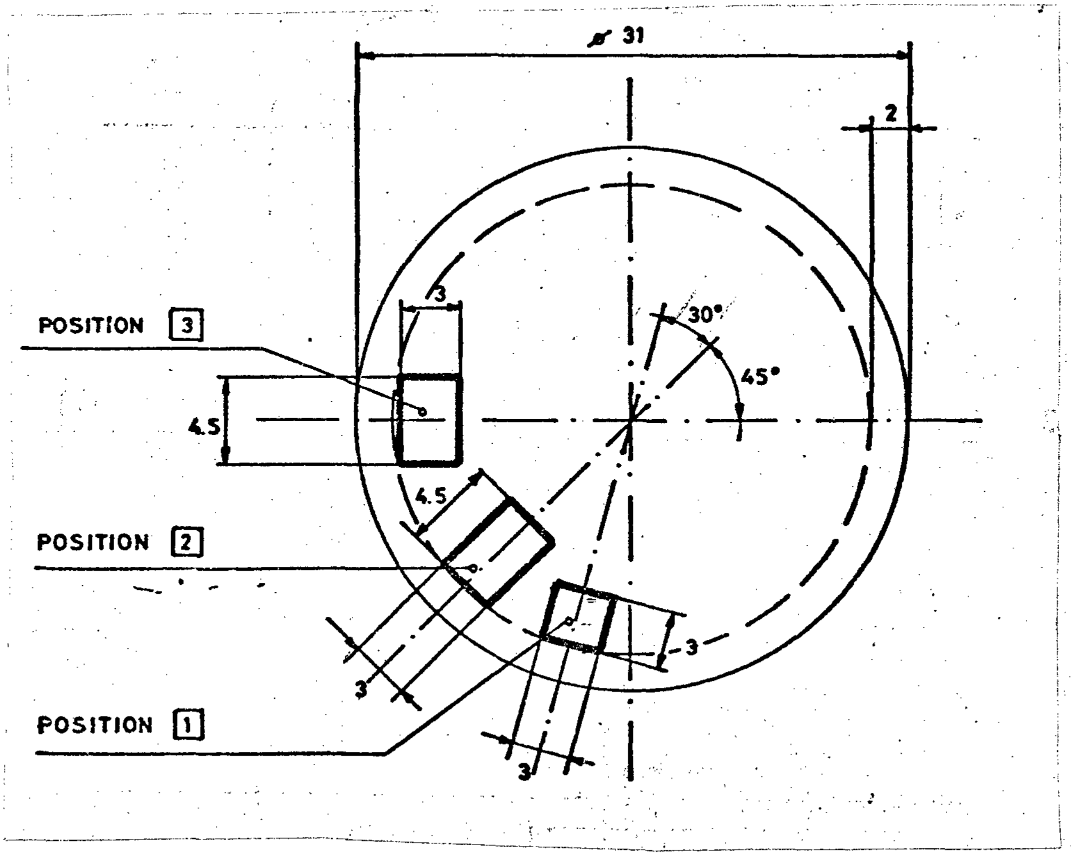
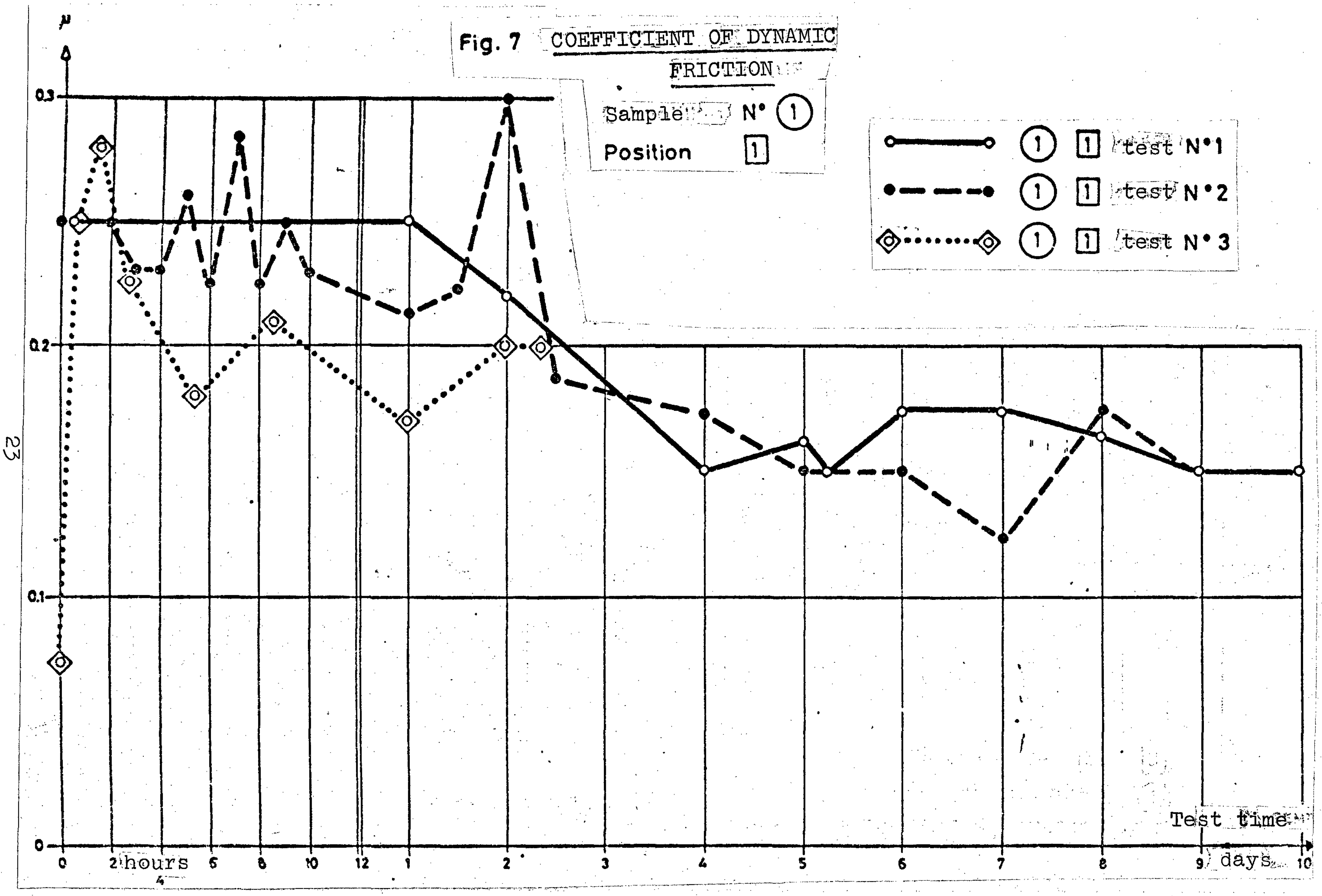


Fig. 6. ARRANGEMENT AND DIMENSIONS OF BRUSHES RELATIVE TO SURFACE OF SAMPLE

Fig. 7 COEFFICIENT OF DYNAMIC FRICTION



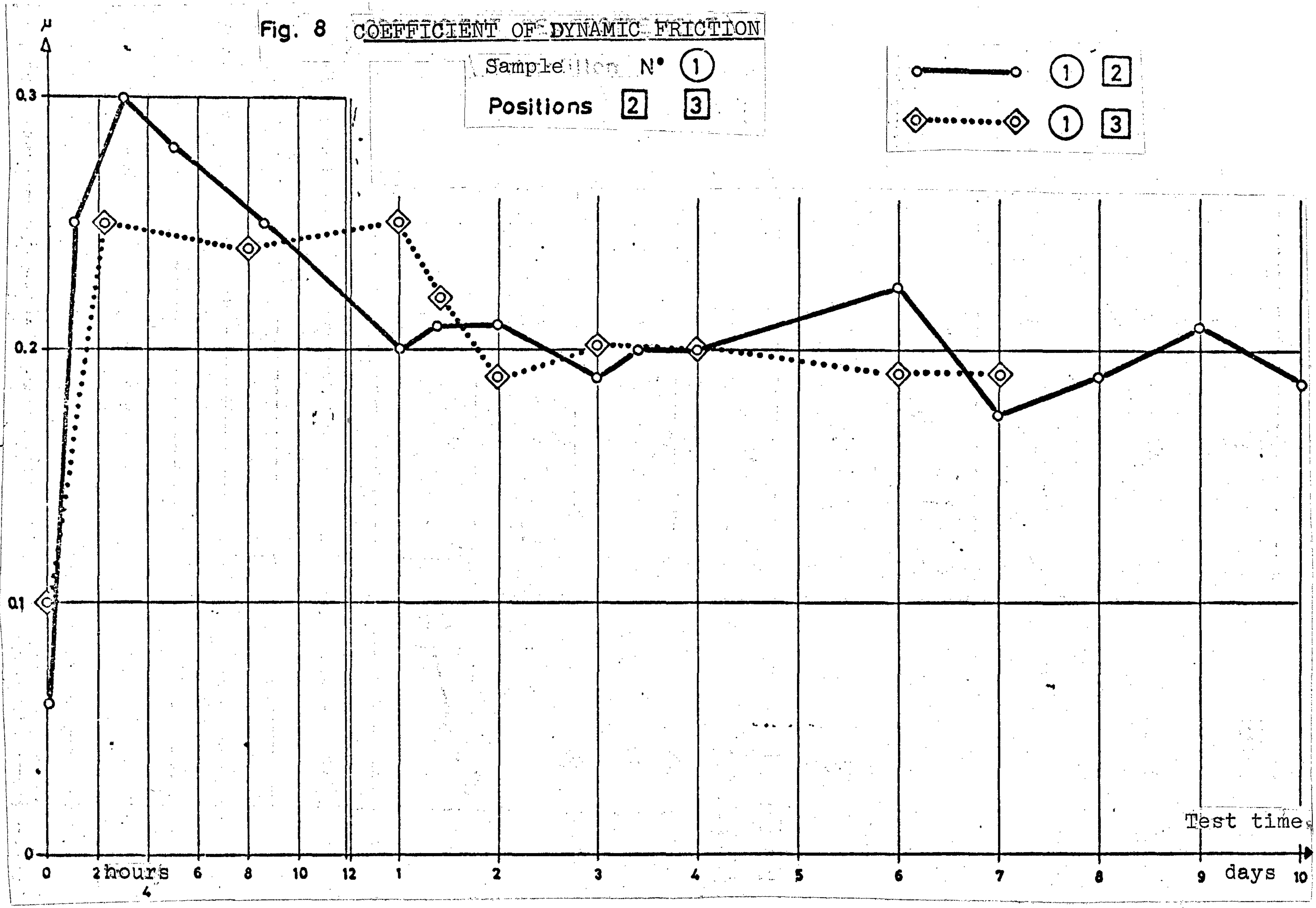


Fig. 8 COEFFICIENT OF DYNAMIC FRICTION

Fig. 9 COEFFICIENT OF DYNAMIC FRICTION

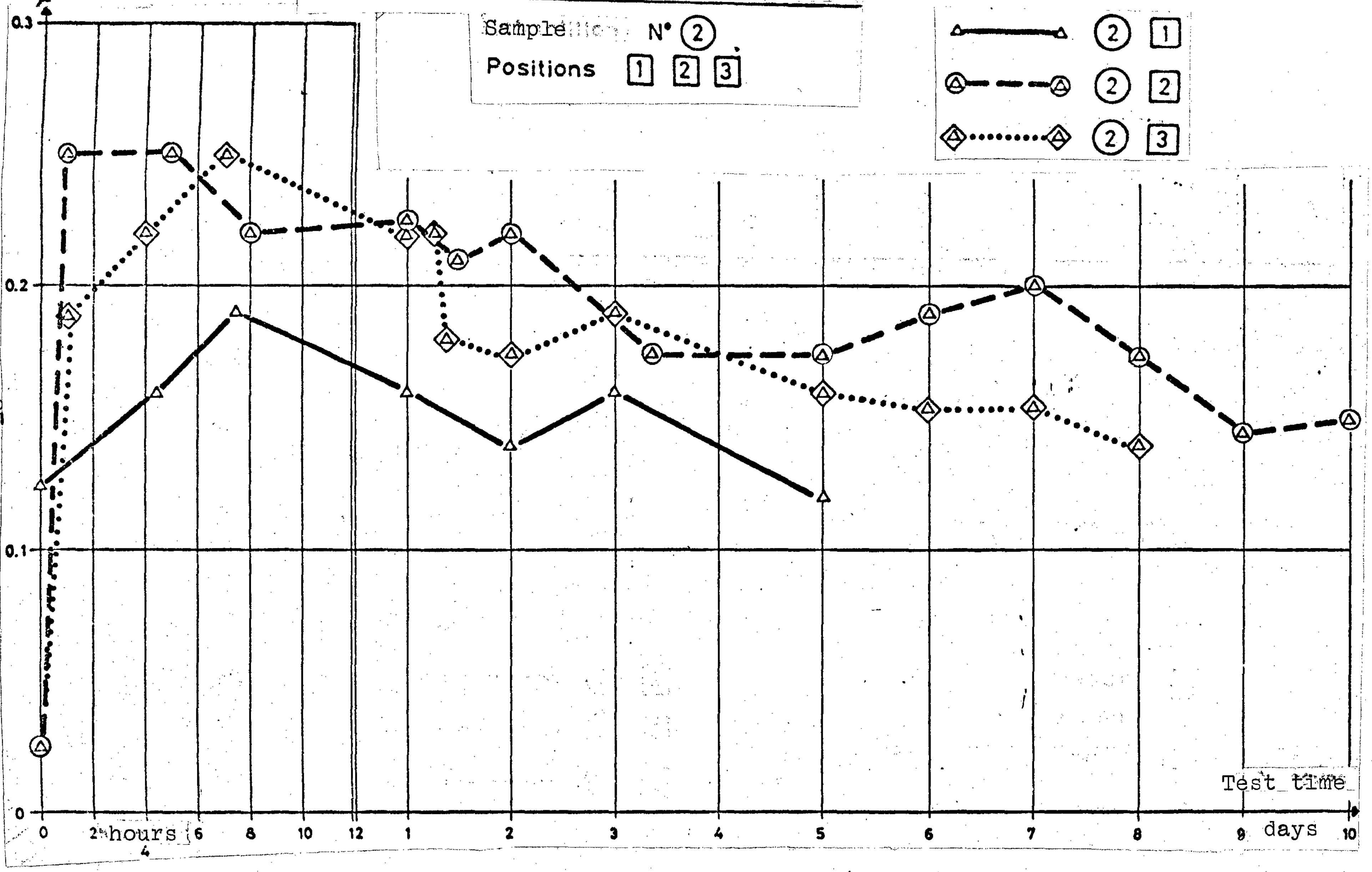


Fig. 10 COEFFICIENT OF DYNAMIC FRICTION

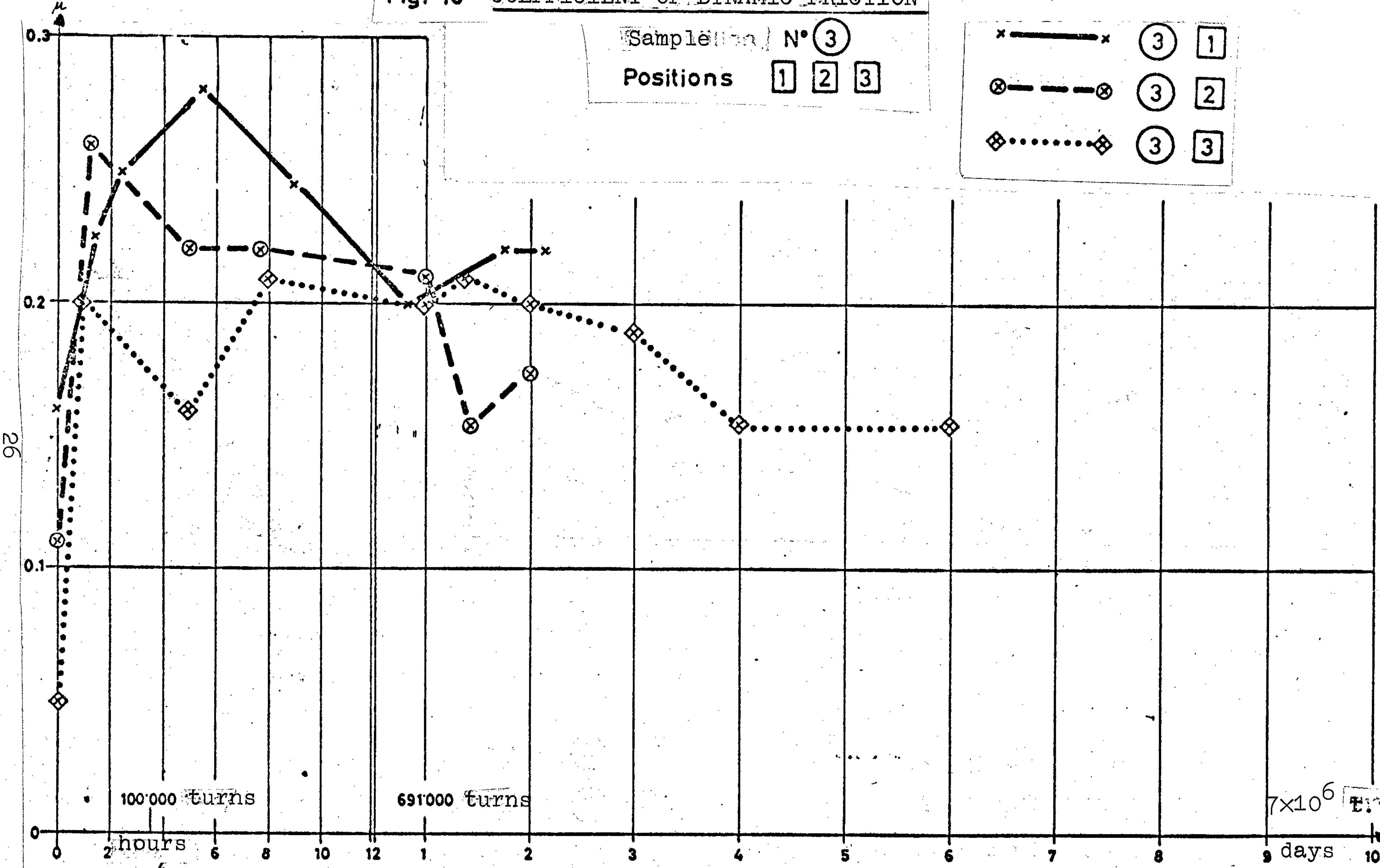
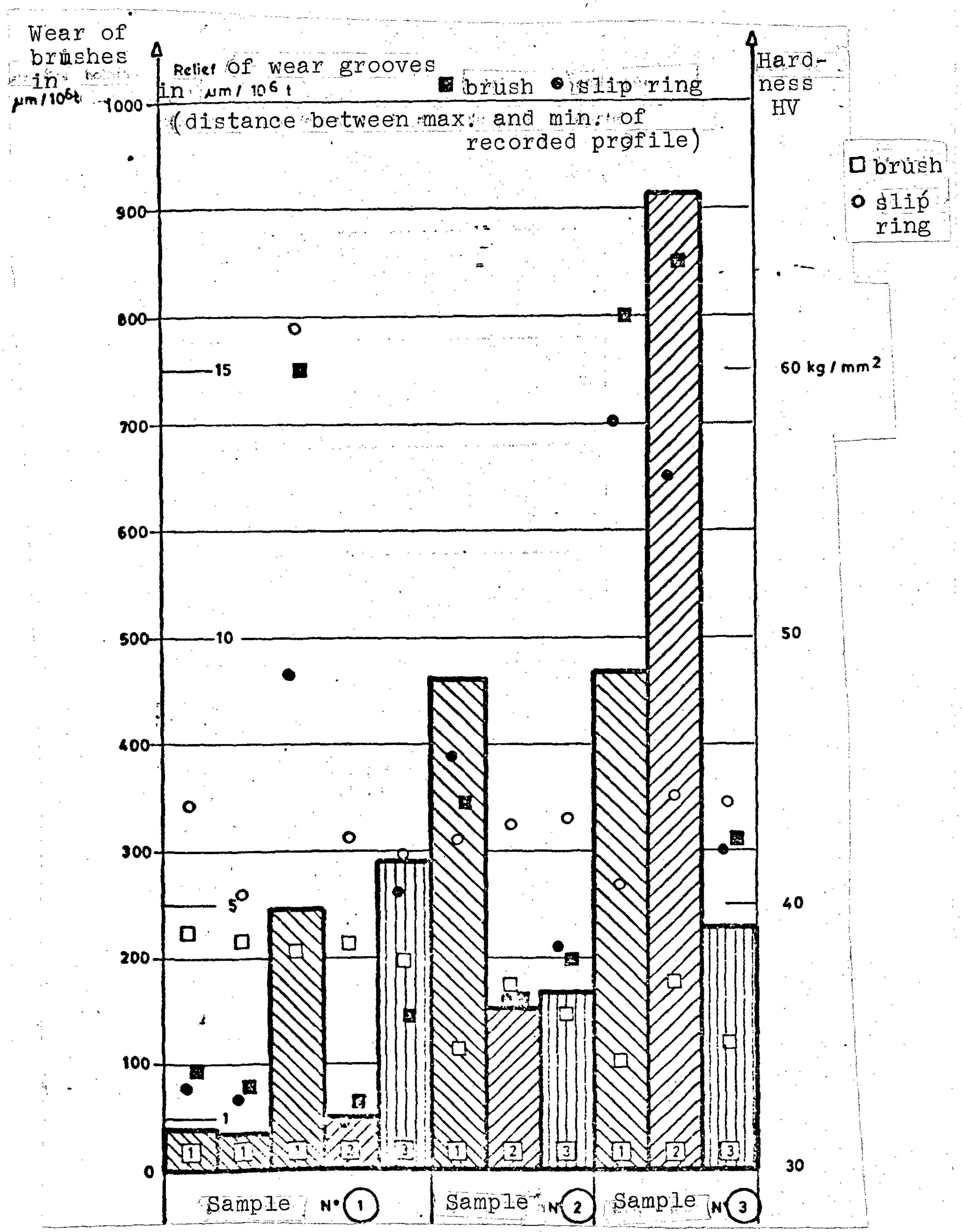


Fig. 11. WEAR OF BRUSHES - DEPTH OF WEAR GROOVES - HARDNESS



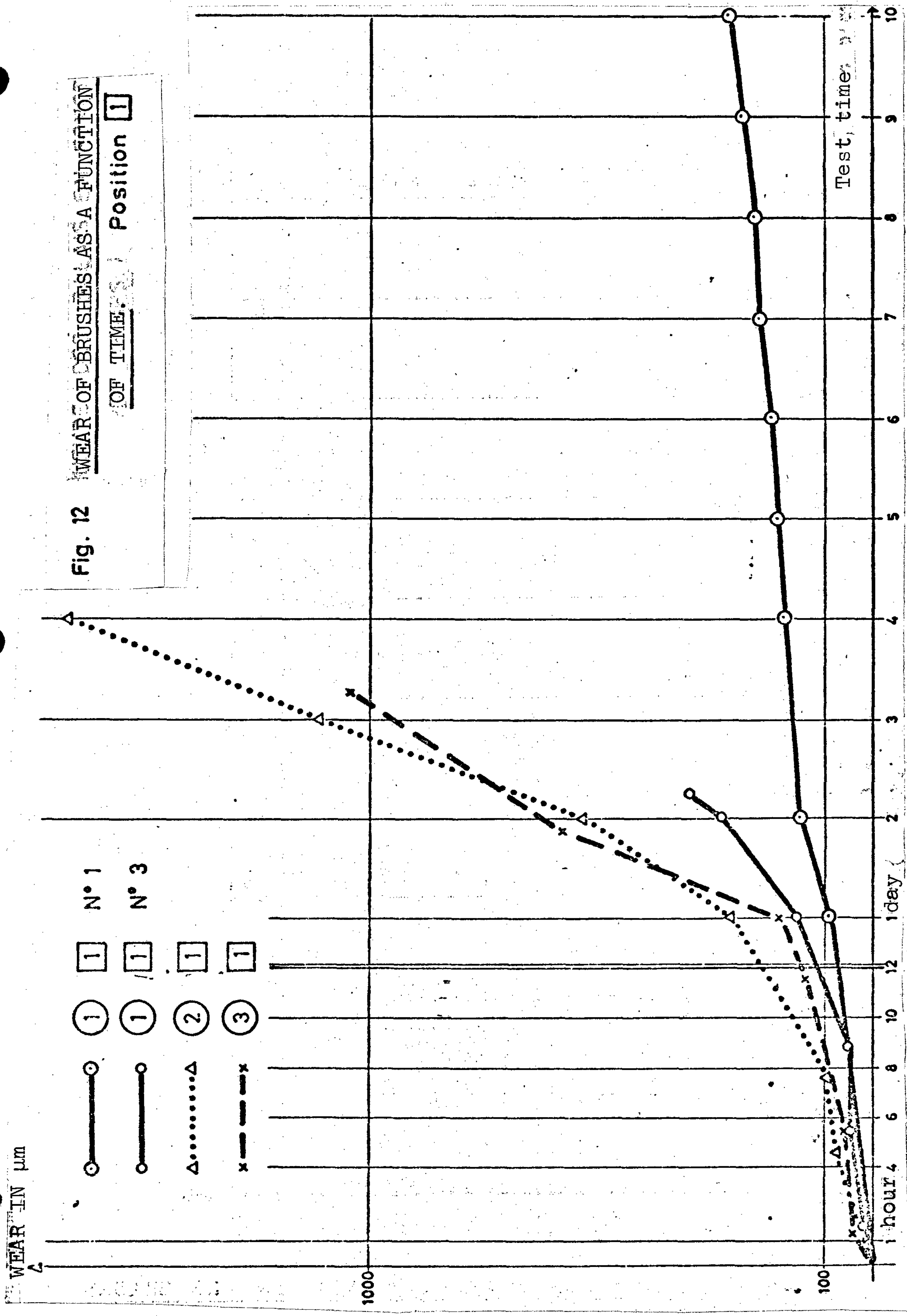
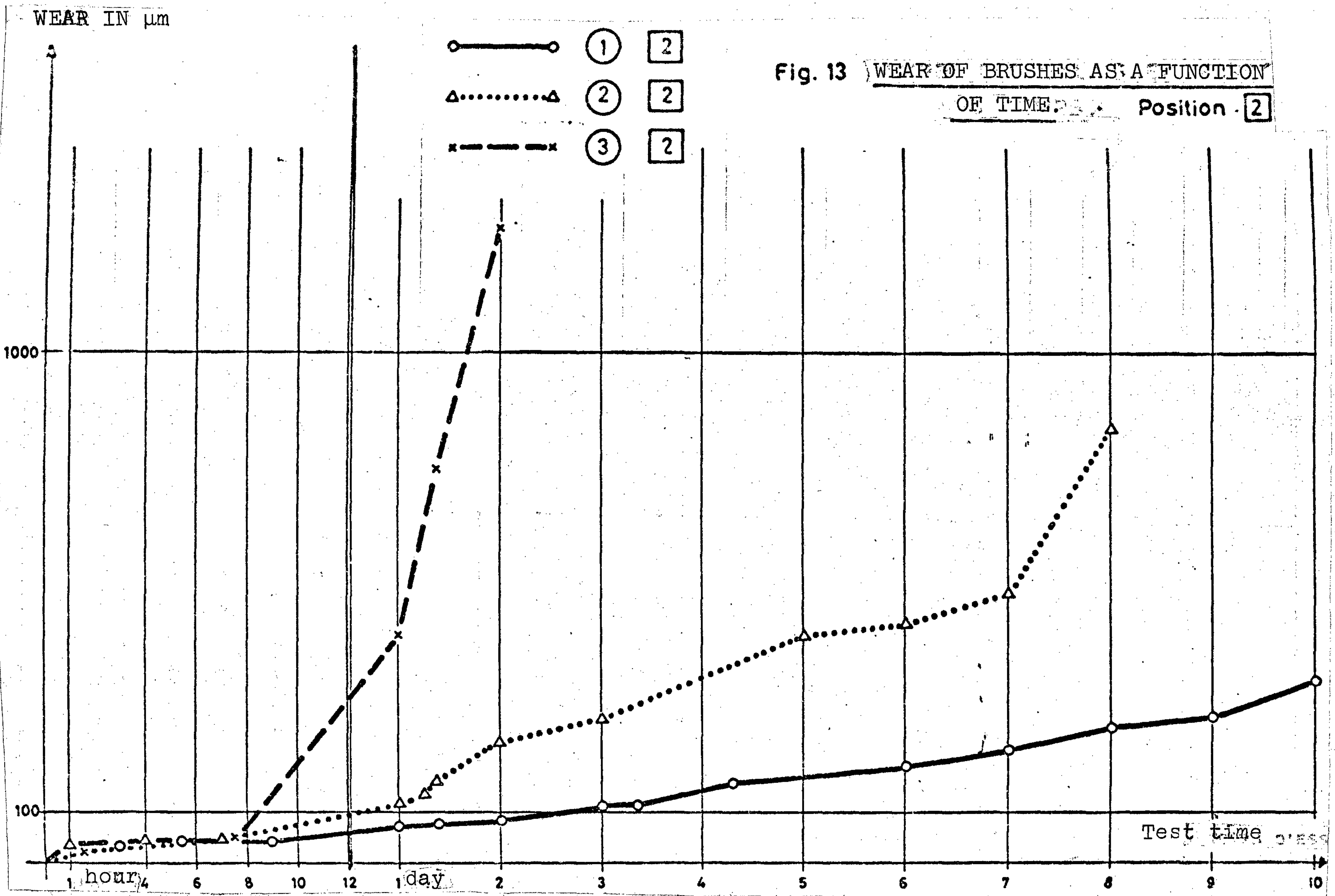


Fig. 12 WEAR OF BRUSHES AS A FUNCTION OF TIME. Position 1

Fig. 13 WEAR OF BRUSHES AS A FUNCTION OF TIME Position 2



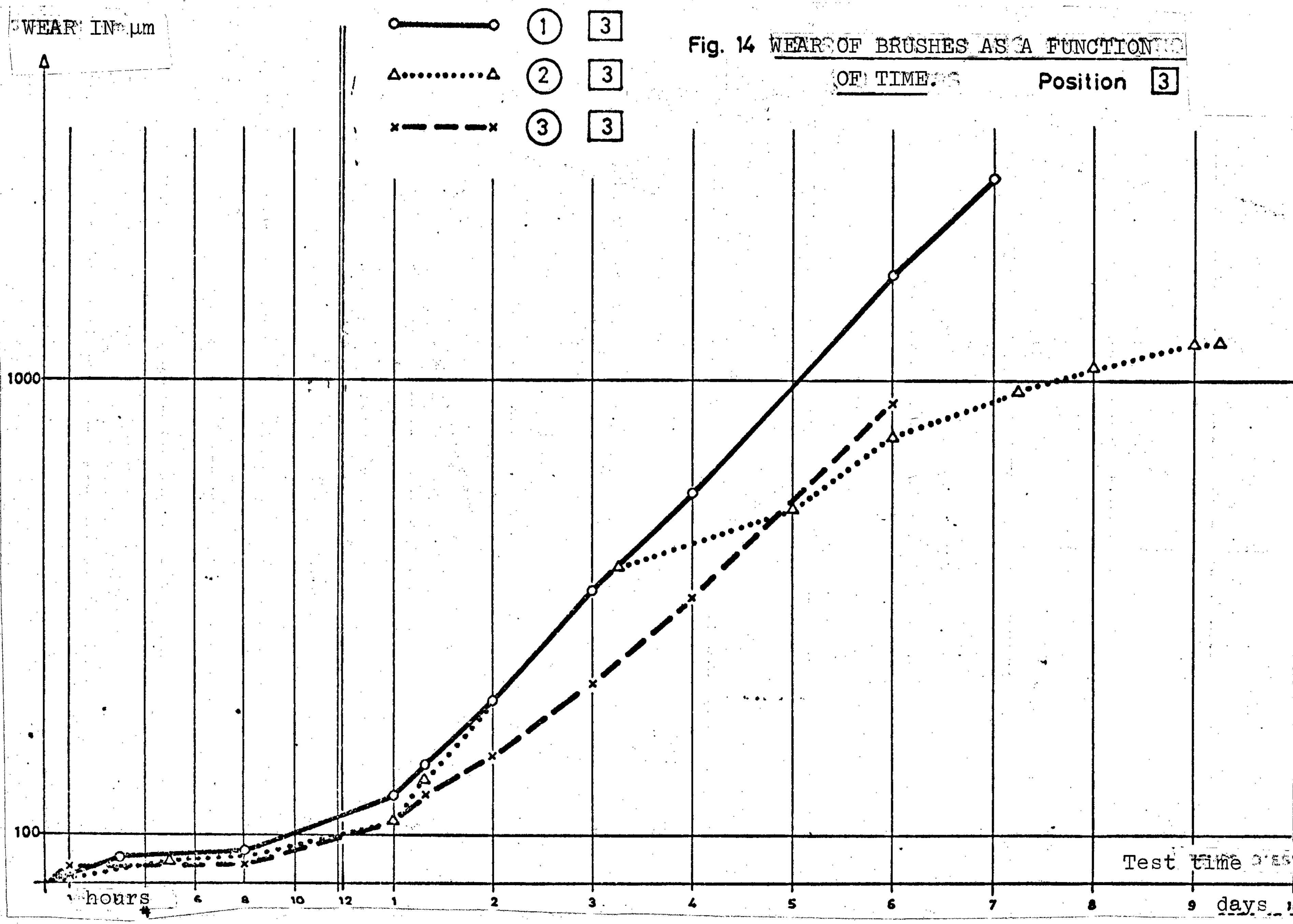
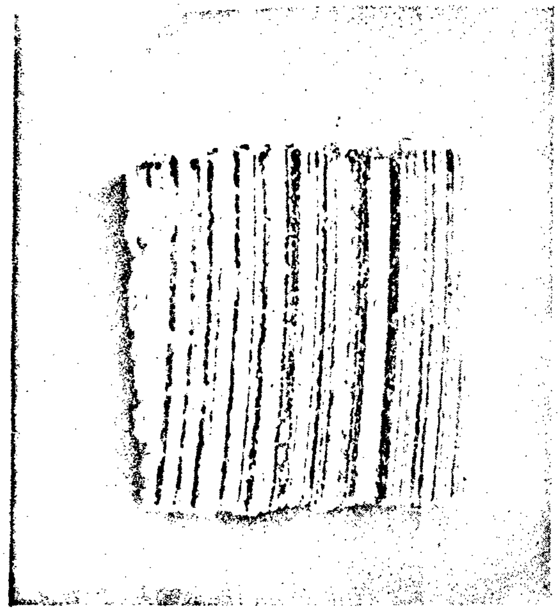


Fig. 14 WEAR OF BRUSHES AS A FUNCTION OF TIME Position 3

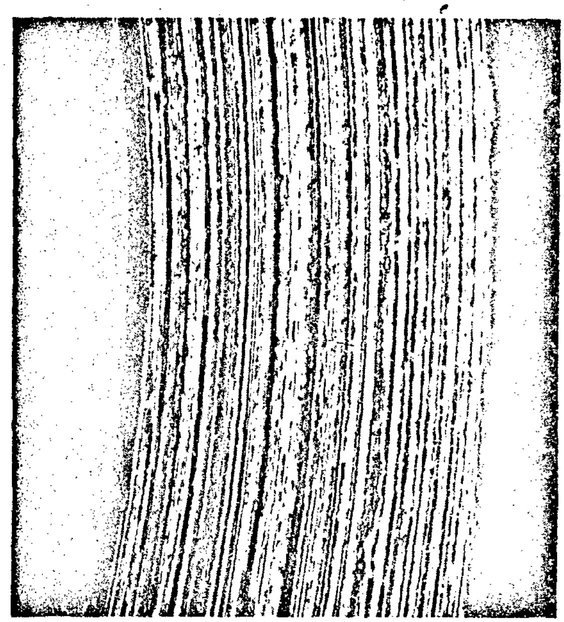
BRUSH: - worn out surface
- wear groove
- structure

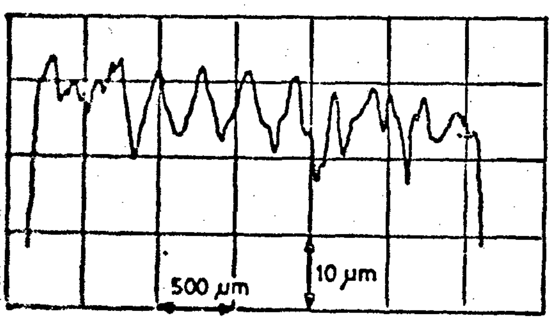
SLIP RING: - worn out surface
- wear groove

N° 4/117 15x



N° 4/113 15x





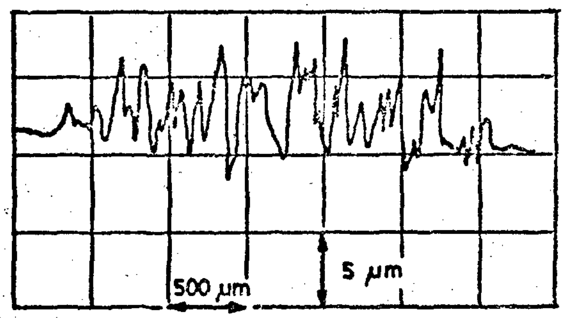


Fig. 15:

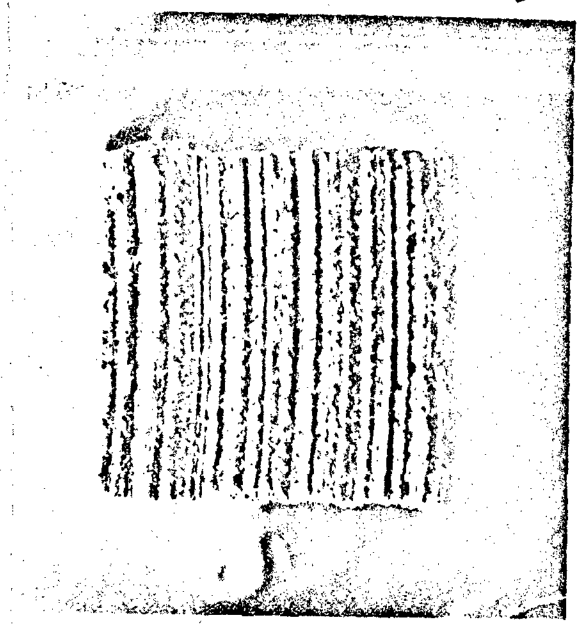
Test 1 [1] 1

7×10^6 turns

Direction of friction

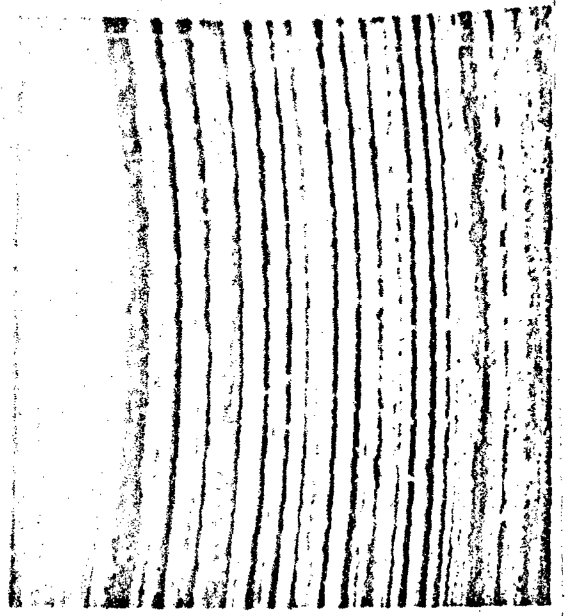
BRUSH: - worn out surface
- wear groove
- structure

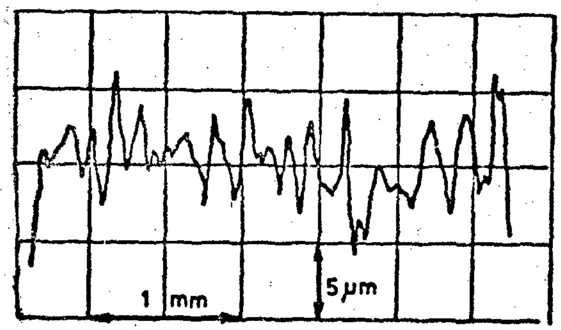
N° 4/1110 15x

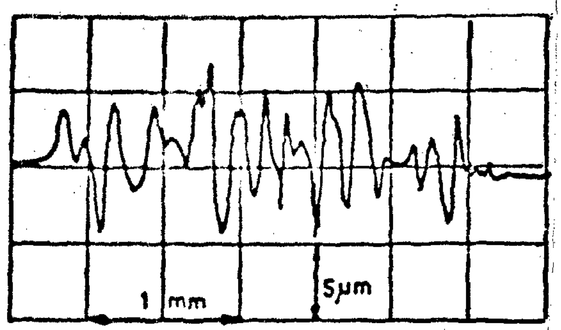


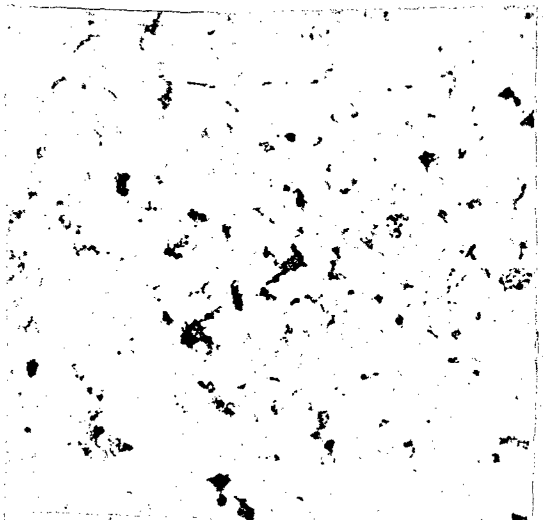
SLIP RING: - worn out surface
- wear groove

N° 4/115 15x









N° 14192 100x

Fig. 16:

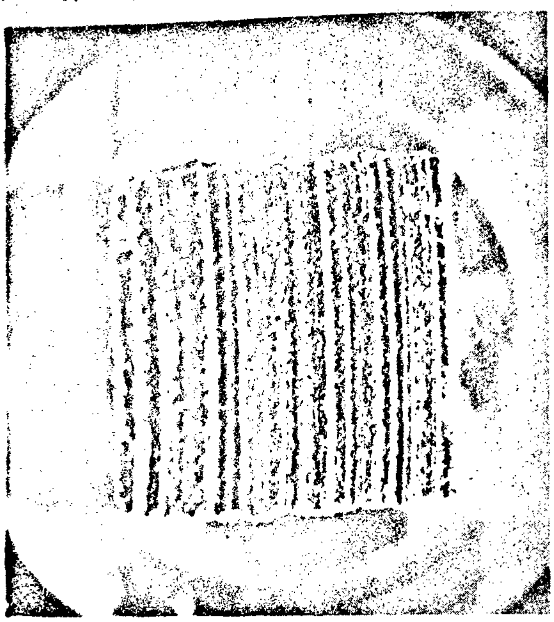
Test 1 $\boxed{1}$ 2

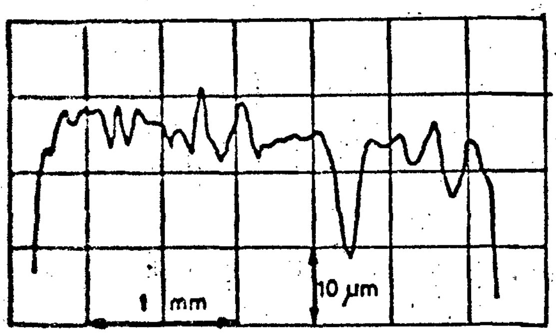
7×10^6 turns

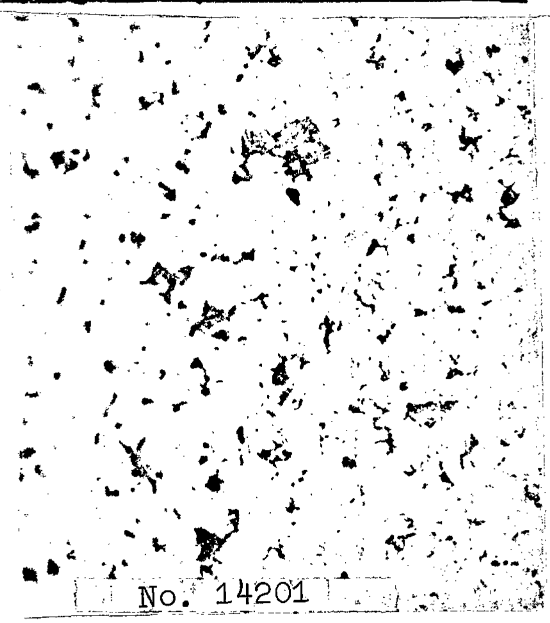
direction of friction

BRUSH: - worn out surface
- wear groove
- structure

N° 4/1232 15x

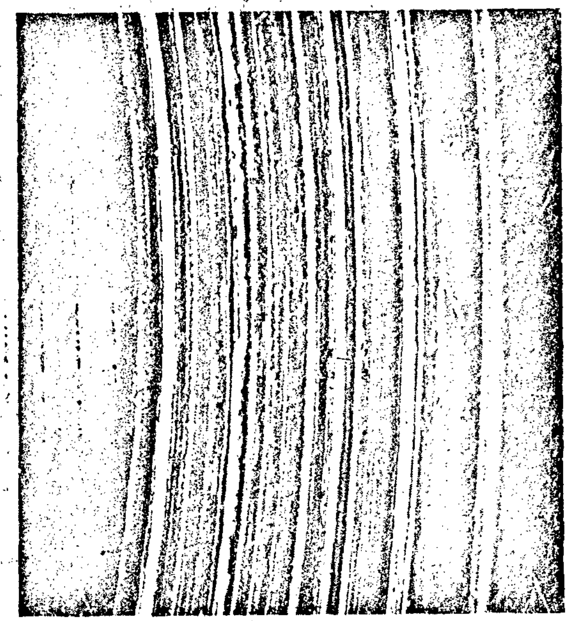






SLIP RING: - worn out surface
- wear groove

N° 4/1238 15x



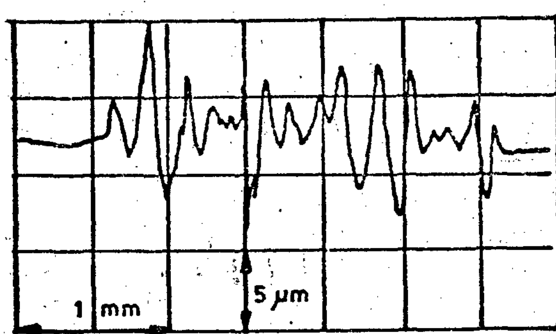


Fig. 17:

Test ① $\boxed{1}$ 3

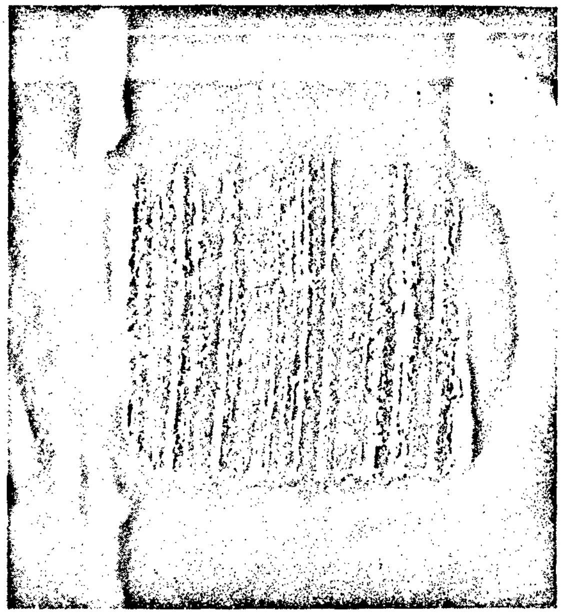
$1,5 \times 10^6$ turns

direction of friction

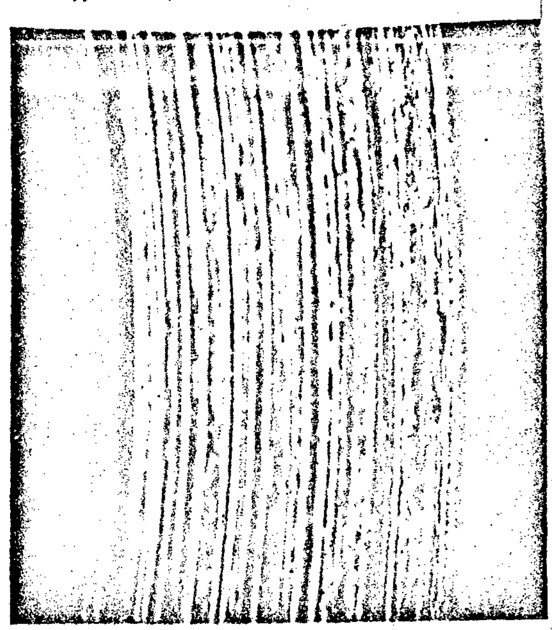
BRUSH: - worn out surface
- wear groove
- structure

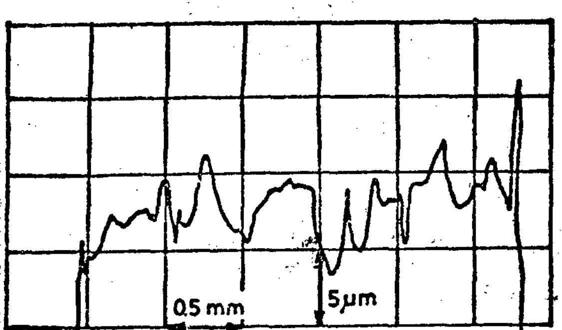
SLIP RING: - worn out surface
- wear groove

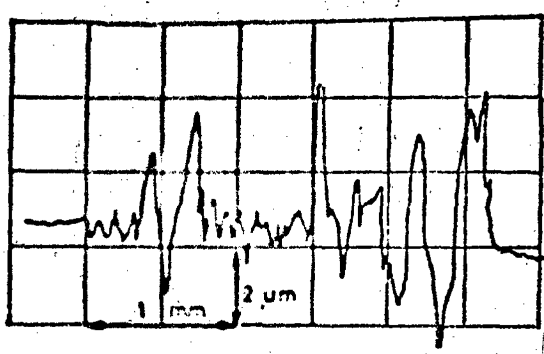
N° 4/1114 15x

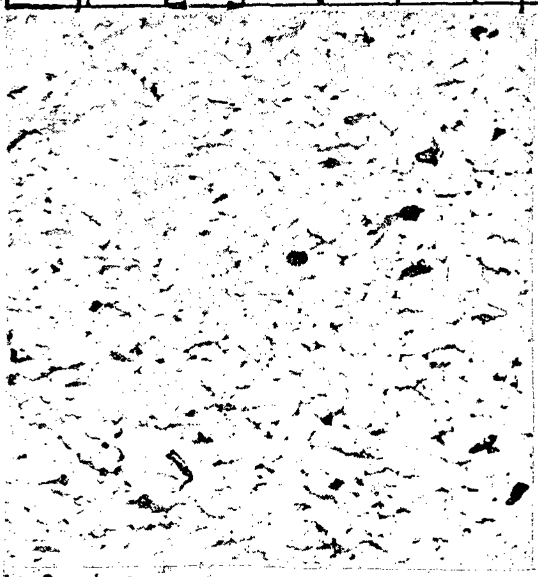


N° 4/1111 15x









N° 14193 100x

Fig. 18:

Test 1 2

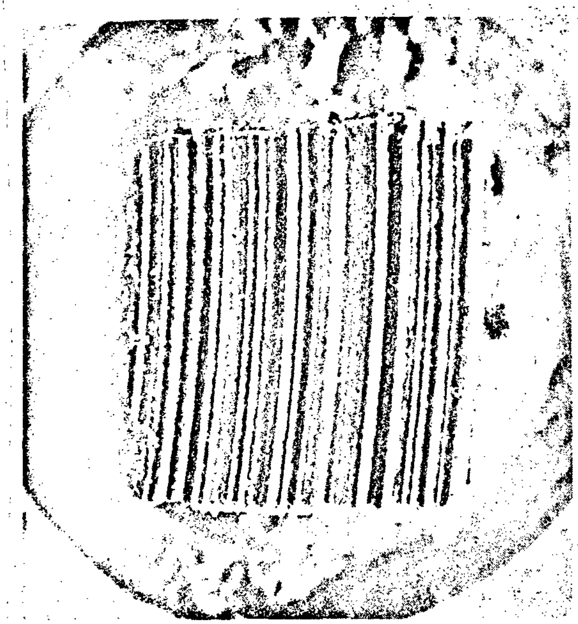
7 x 10^6 turns

direction of friction

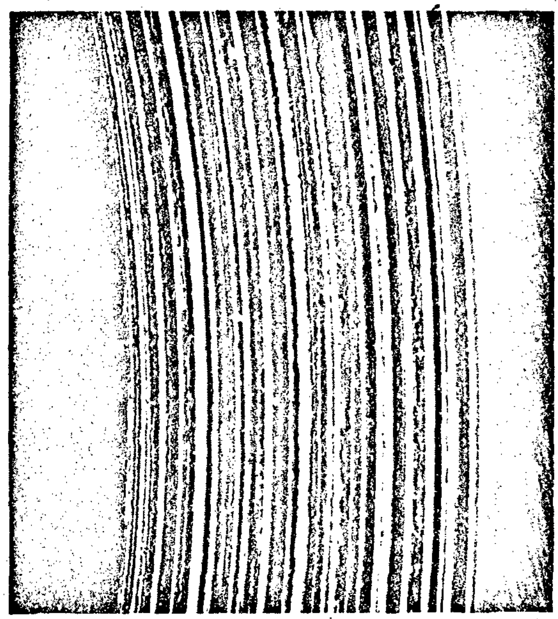
BRUSH: - worn out surface
- wear groove
- structure

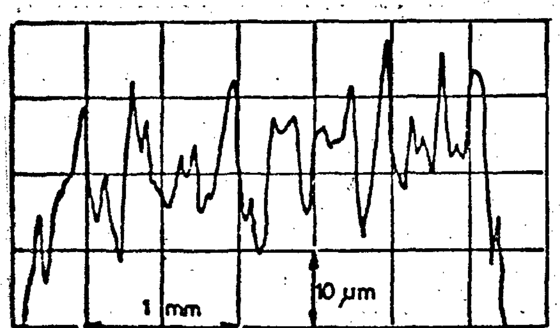
SLIP RING: - worn out surface
- wear groove

N° 4/1118 15x



N° 4/1116 15x





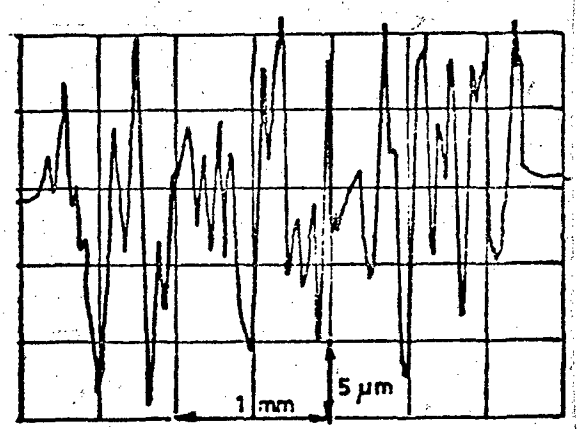


Fig. 19:

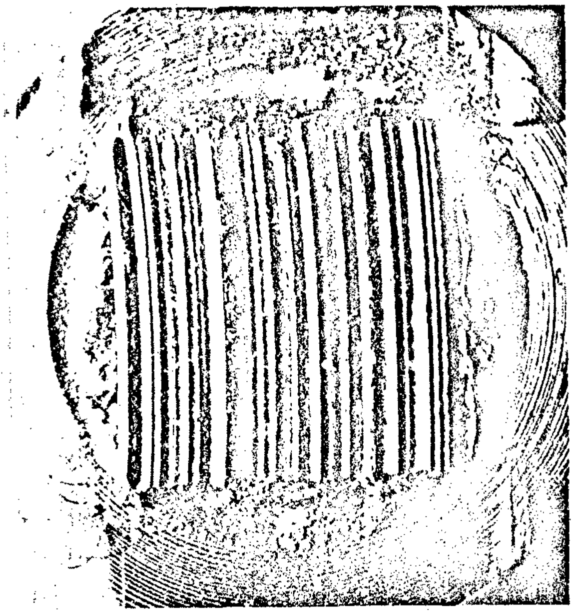
Test 1 3

4,8 x 10^6 turns

direction of friction

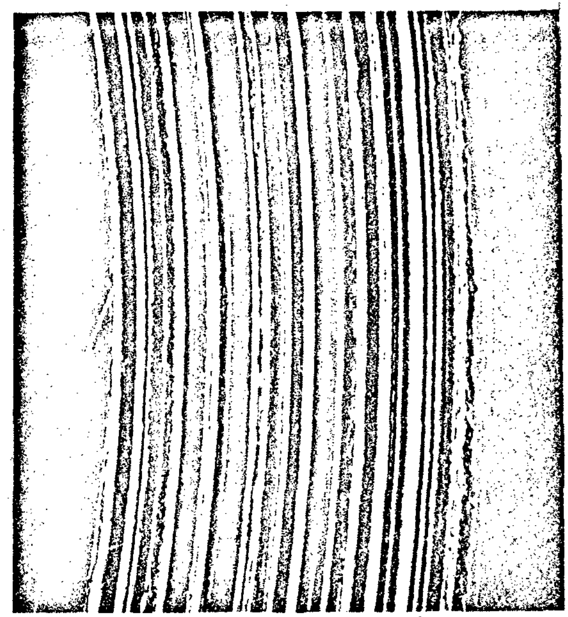
BRUSH: - worn out surface
- wear groove
- structure

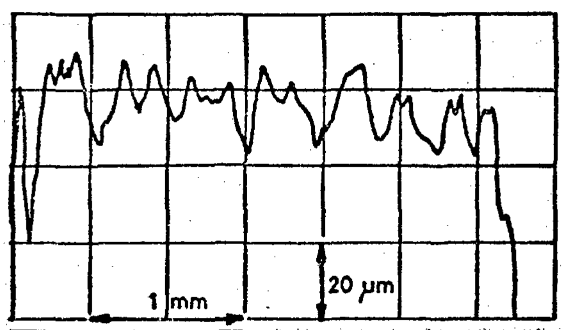
N° 4/1124 15x

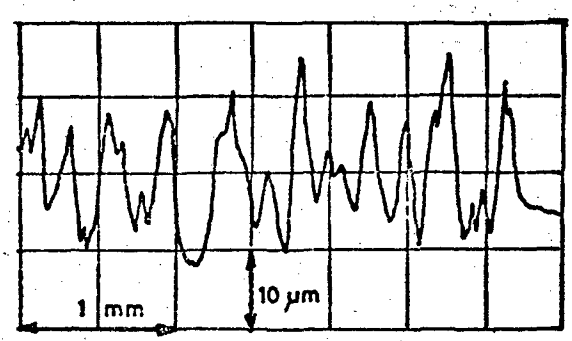


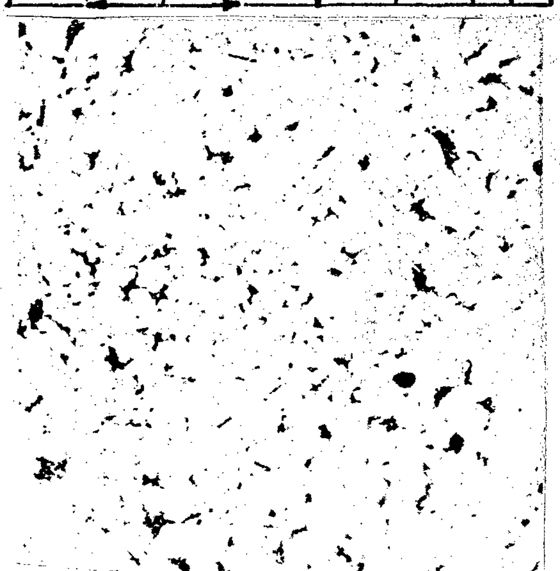
SLIP RING: - worn out surface
- wear groove

N° 4/1120 15x









N° 14214 100x

Fig. 20:

Test 2 1

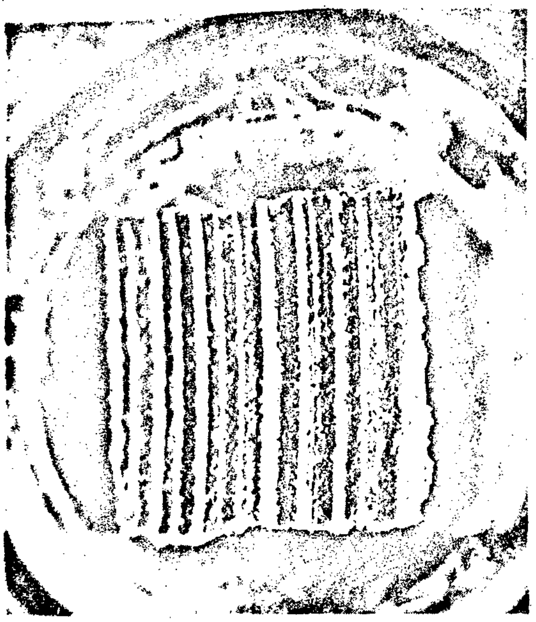
$3,5 \times 10^6$ turns

direction of friction

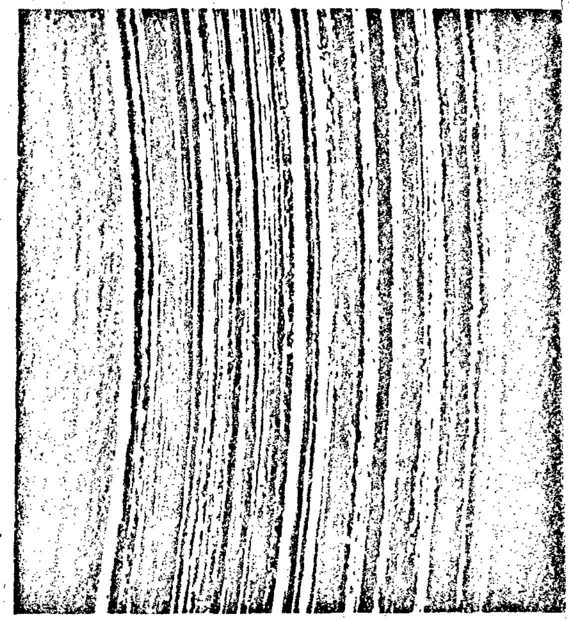
BRUSH: - worn out surface
- wear groove
- structure

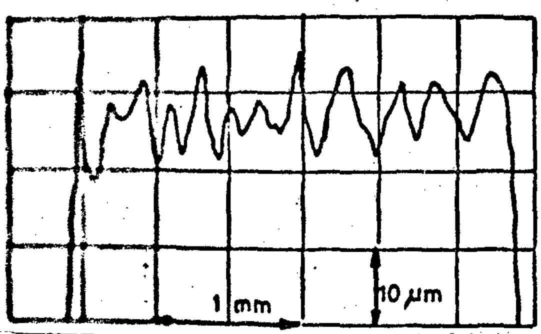
SLIP RING: - worn out surface
- wear groove

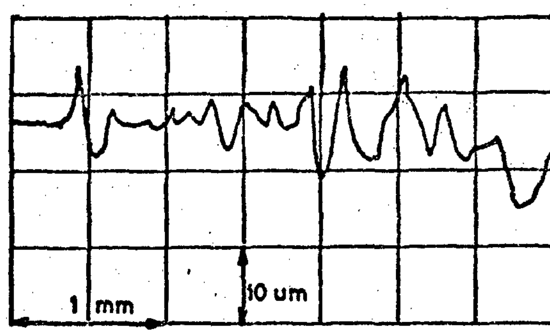
N° 4/1228 15x



N° 4/1233 15x







N° 14216

Fig. 21:

Test ② 2

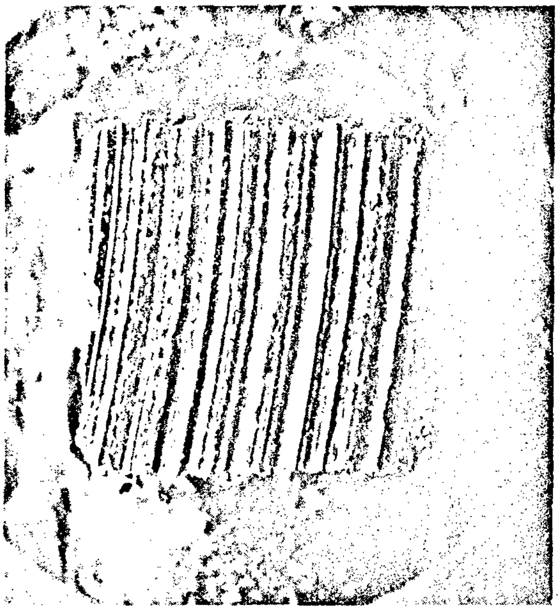
6 x 10^6 turns

direction of friction

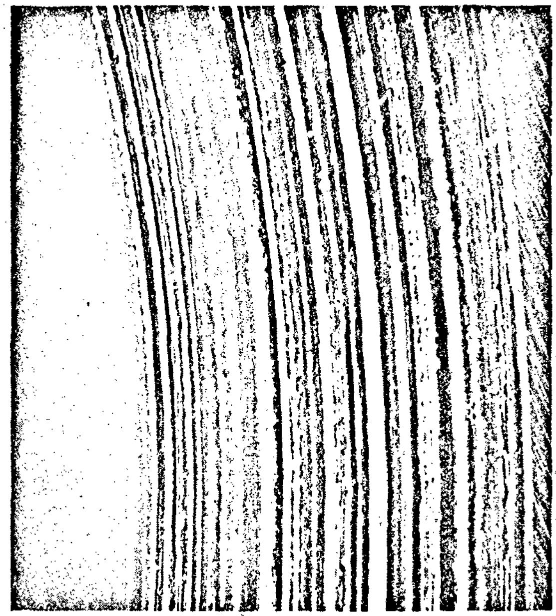
BRUSH: - worn out surface
- wear groove
- structure

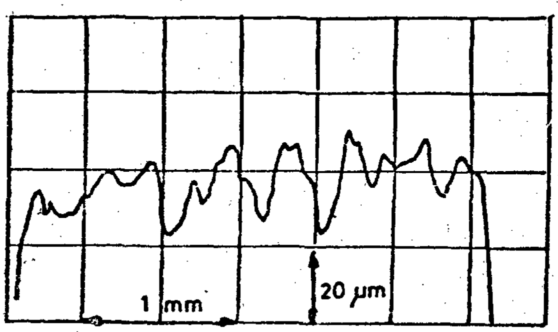
SLIP RING: - worn out surface
- wear groove

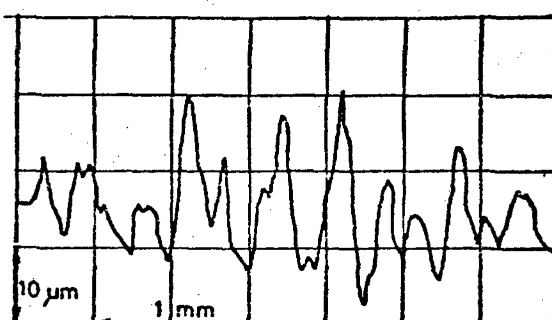
N° 4/1127 15x



N° 4/1122 15x







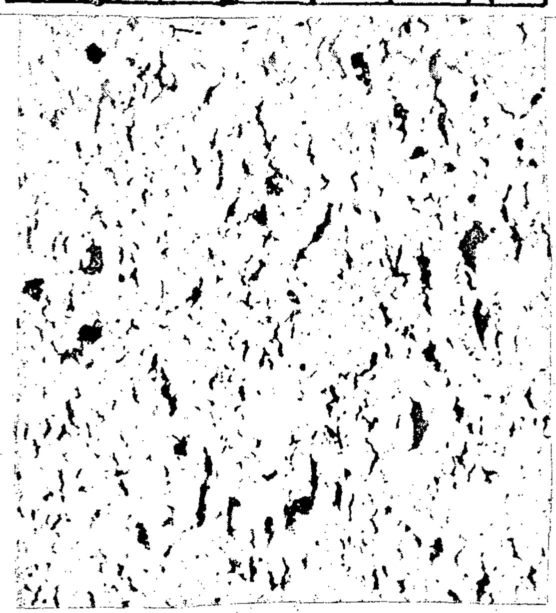


Fig. 22:

Test 2 3

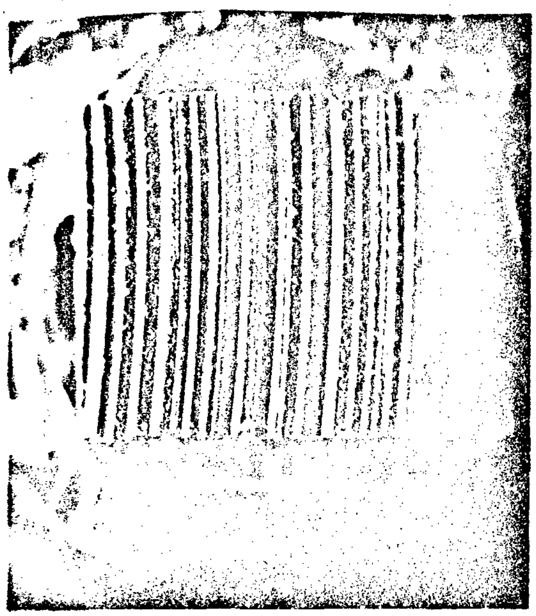
6 x10^6 turns

direction of friction

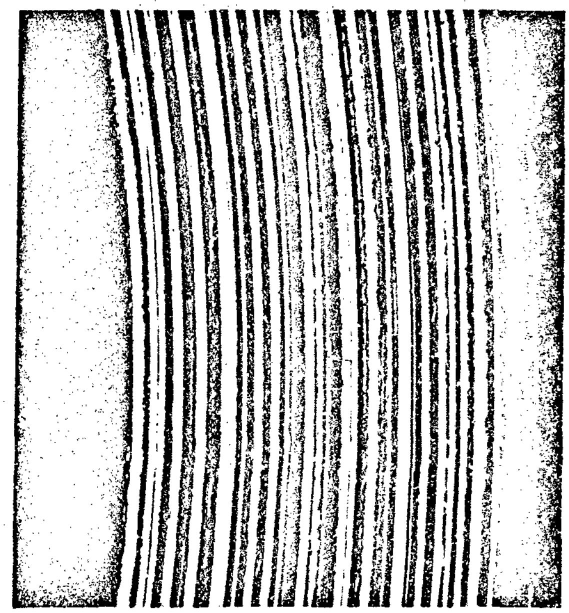
BRUSH: - worn out surface
- wear groove
- structure

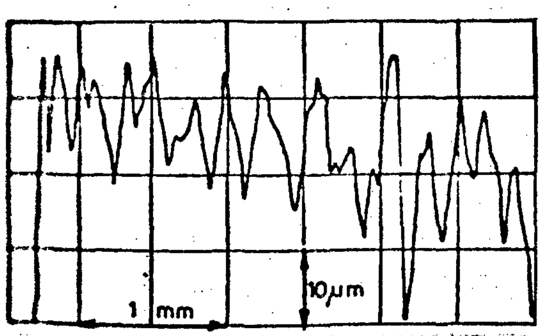
SLIP RING: - worn out surface
- wear groove

N° 4/1229 15x



N° 4/1234 15x





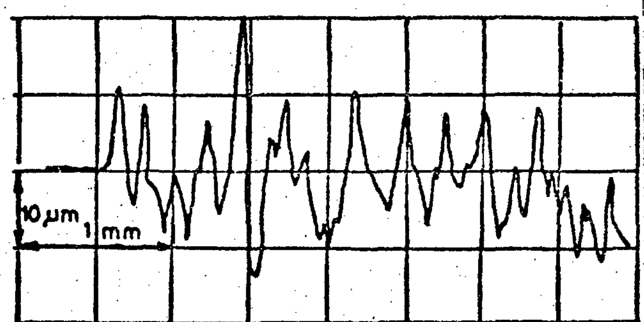


Fig. 23:

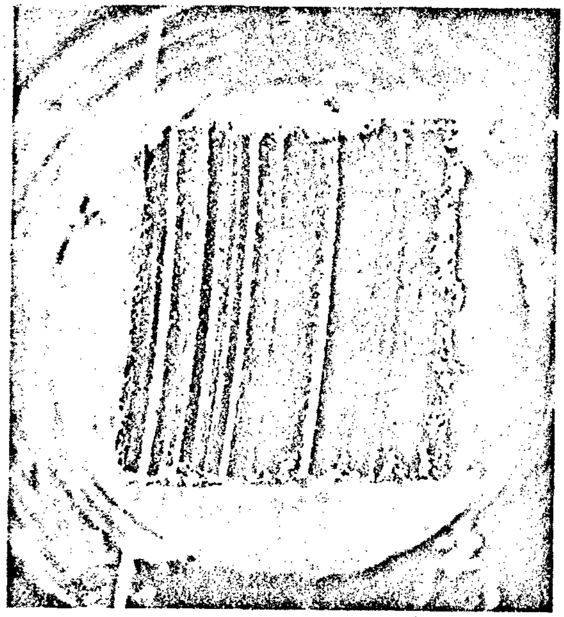
Test 3 1

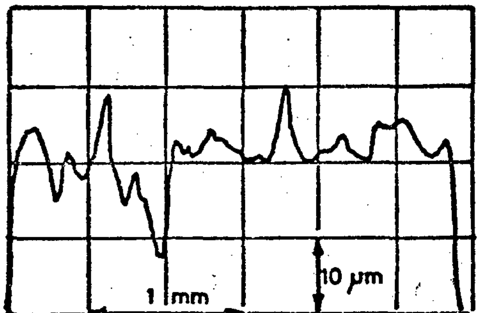
2 x10^6 turns

direction of friction

BRUSH: - worn out surface
- wear groove
- structure

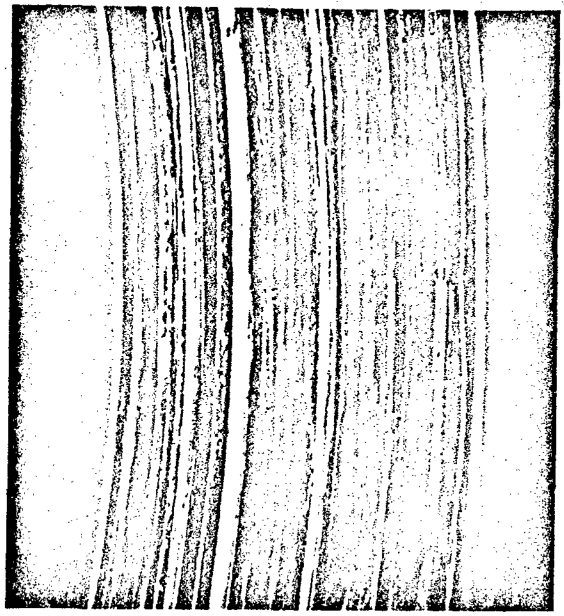
N° 4/1230 15x





SLIP RING: - worn out surface
- wear groove

N° 4/1235 15x



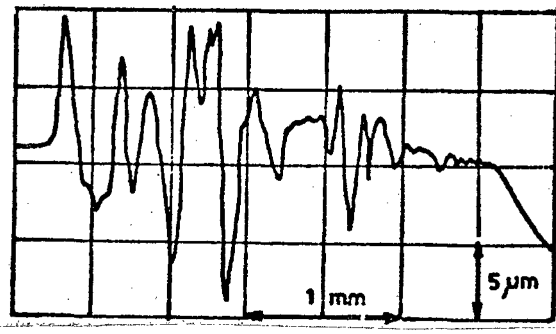


Fig. 24:

Test 3 2

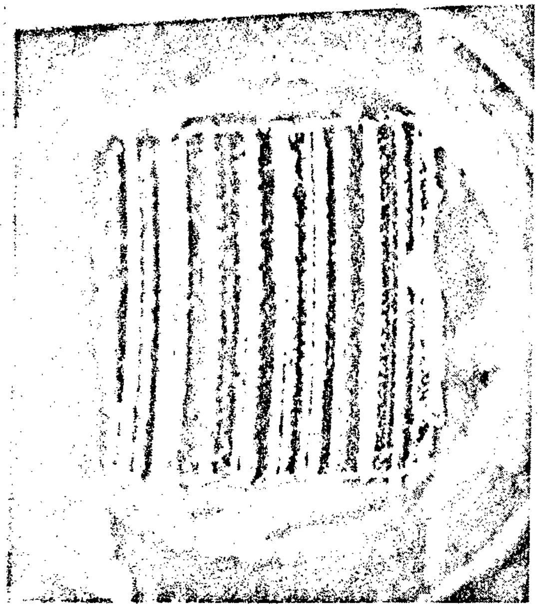
1,4 x10^6 turns

direction of friction

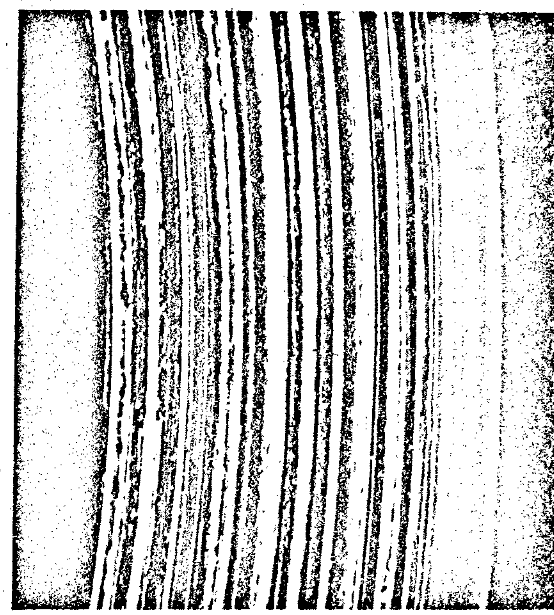
BRUSH: - worn out surface
- wear groove
- structure

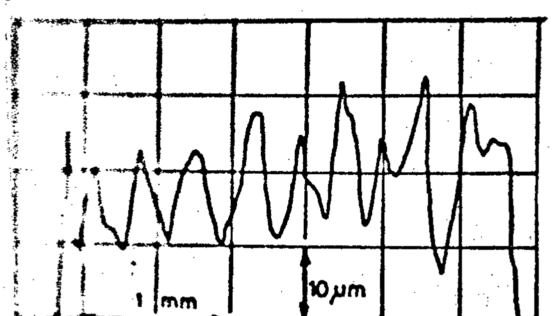
SLIP RING: - worn out surface
- wear groove

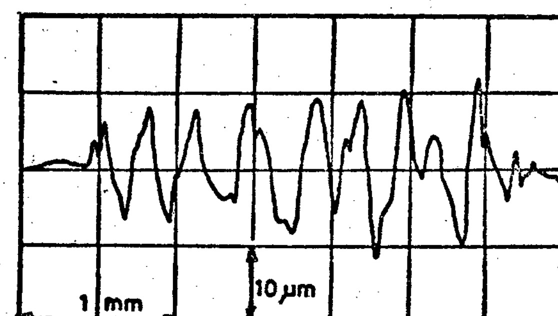
N° 4/1231 15x



N° 4/1237 15x







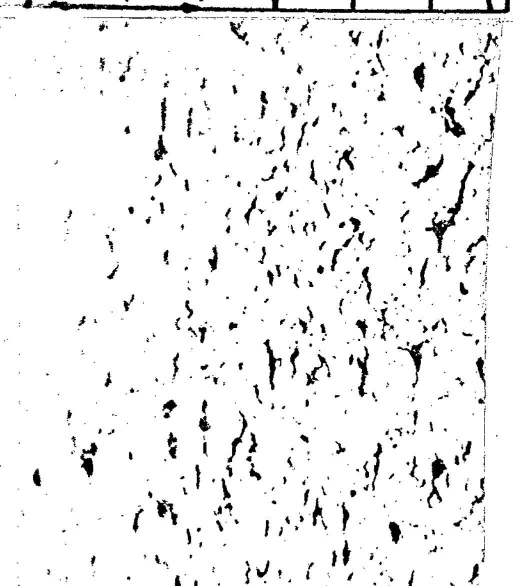
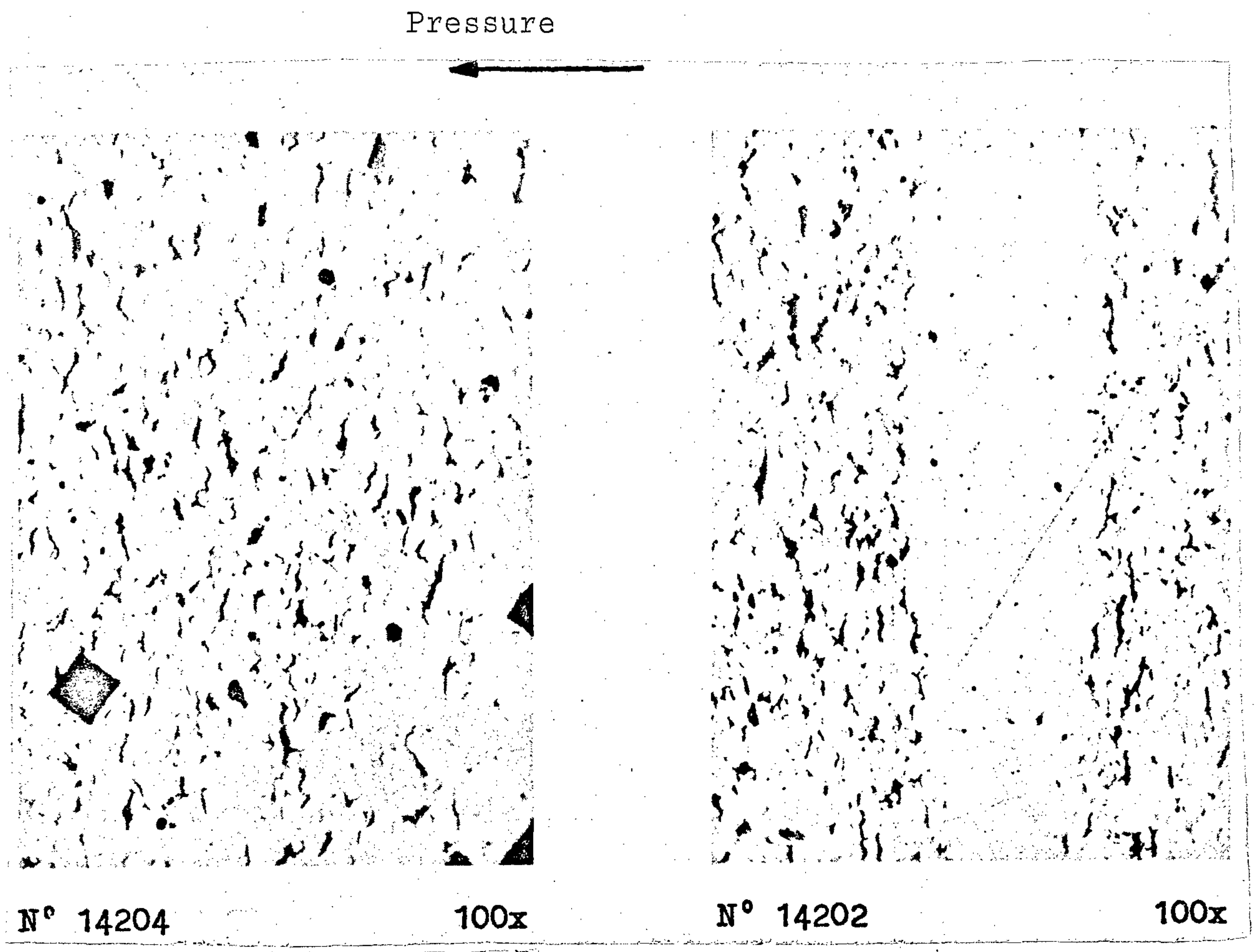


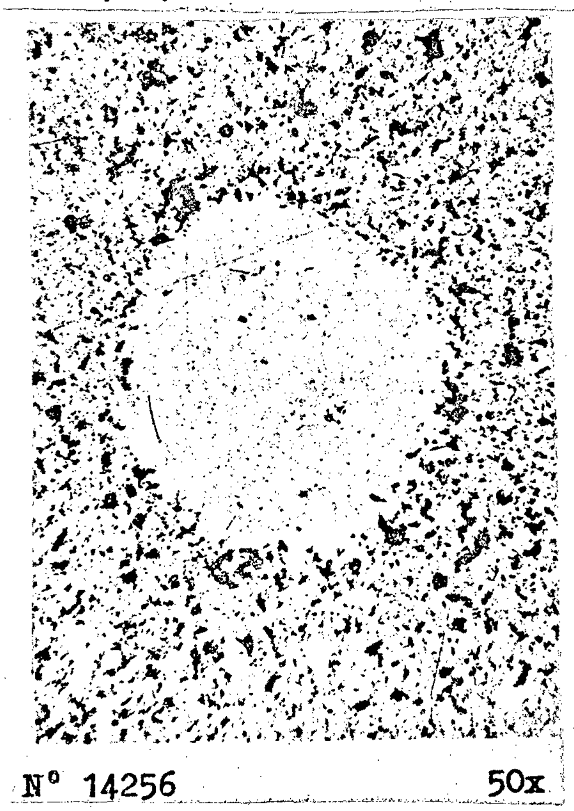
Fig. 25:

Test 3 3

4×10^6 turns

direction of friction





Pressure perpendicular
to surface

Fig. 26. Appearance of silver spots found in the structure of the brushes.

N° 14221 100x

N° 13734 100x

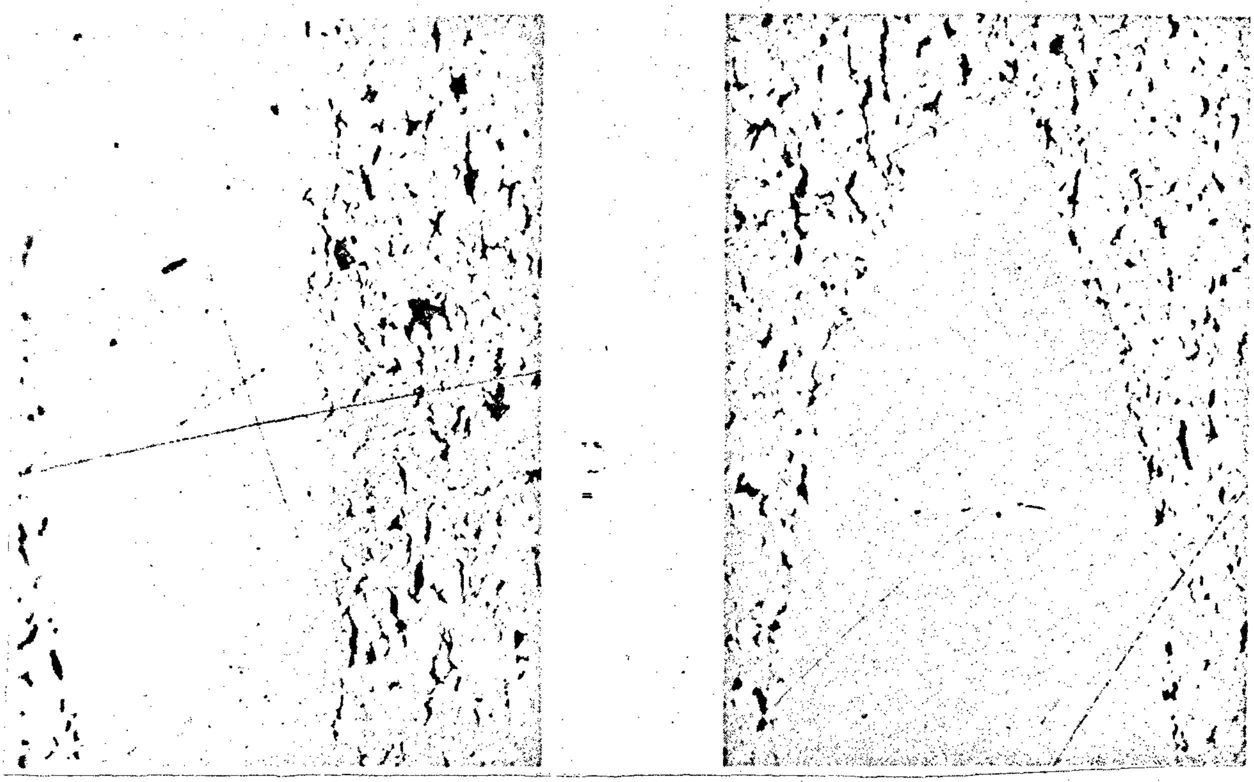
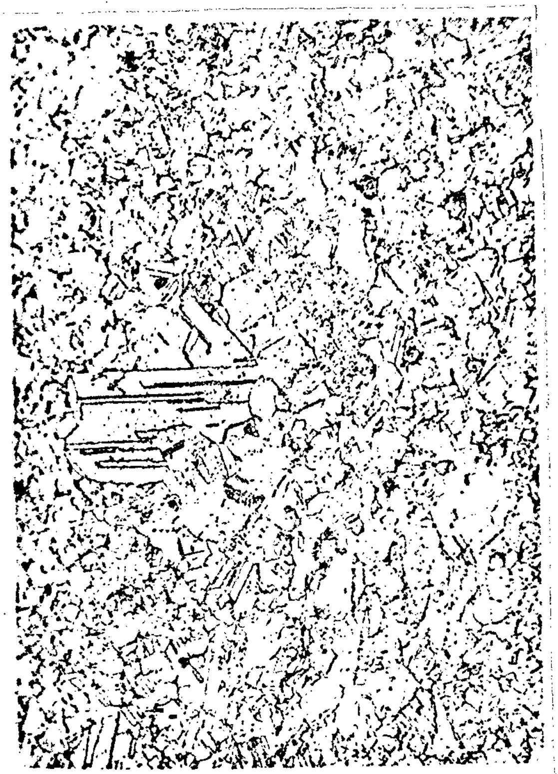


Fig. 27. Appearance of other spots in the brushes.



N° 14257 250x

Microphotograph of a slip ring

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